Section I

EARTHQUAKE DAMAGE

INTENSITY DISTRIBUTION AND ISOSEISMAL MAP FOR
THE MORGAN HILL, CALIFORNIA, EARTHQUAKE OF APRIL 24, 1984

by

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ABSTRACT

The Morgan Hill, California, earthquake of April 24, 1984 had a Modified Mercalli (MM) intensity of VII or more over a 340 km^2 area enclosing Coyote, Morgan Hill, and San Martin. Maximum intensity VIII effects occurred on Oakridge Court and Oakridge Lane, two short streets in the Jackson Oaks subdivision located in eastern Morgan Hill. The earthquake was felt over an area of about 120,000 km^2 of the land area in California and western Nevada. Damage was estimated at $7.5 million.

INTRODUCTION

The Morgan Hill earthquake of April 24, 1984 was felt over a land area of approximately 120,000 km^2 in California and western Nevada (fig. 1). The University of California at Berkeley (BRK) located the earthquake at latitute $37^{\circ}19.2'$ N., longitude $121^{\circ}41.9'$ W., with a focal depth of 8 km. This epicenter is very close to the Calaveras Fault at a point 22 km north of Morgan Hill and 18 km east of San Jose.

This is a preliminary report on the intensity distribution as shown on the isoseismal map (fig. 1). The isoseismal map was compiled from data obtained from a questionnaire canvass of postmasters and police departments (within 150 km of the epicenter), supplemented with information from numerous press reports. Intensities were rated using the Modified Mercalli (MM) Intensity Scale of 1931 (Wood and Neumann, 1931).

No fatalities were attributed to this earthquake; however, 21 people required hospital treatment for injuries. Most of the damage occurred in Santa Clara County, where the most serious damage extended from south San Jose to San Martin, a distance of about 37 km. The California Office of Emergency Services reported that 276 homes (including mobile homes) and 20 businesses were damaged to some degree by the shock and estimated the total loss due to the earthquake at $7.5 million. The most severe damage occurred in the Jackson Oaks subdivision, located near Anderson Lake, about 13 km east of Morgan Hill, where five homes suffered extensive damage; two of them were condemned. Jackson Oaks is geographically situated in an area of low hills; and these homes were located on two short streets, Oakridge Court and Oakridge Lane, that are about midway between the crest and valley of a hill. Intensity VIII effects were assigned to this small area, an area too small to be delineated in figure 1. Morgan Hill reported damage to 47 single-family homes, 42 mobile homes, and many businesses.

[1]U.S. Geological Survey, Denver, Colorado

This earthquake is the largest to have occurred on the Calaveras Fault since the magnitude 6.6 M_L(BRK) event of July 1, 1911 at latitude 37.25° N., longitude 121.75° W., a location very near the epicenter of the Morgan Hill earthquake. The 1911 earthquake was given a Rossi-Forel (RF) intensity of VIII (MM VII) (Anonymous, 1911) and an intensity of RF IX (VIII MM) (Wood, 1912). An exact comparison of the intensity patterns is not possible since an isoseismal map for the 1911 earthquake is not available; however, Coffman and others (1982) estimated the felt area as 60,000 mi^2 (155,000 km^2) for the 1911 shock which had a magnitude M_L = 6.6(BRK). In comparison, a felt area of about 120,000 km^2 was estimated for the Morgan Hill earthquake, which had an M_L magnitude of 6.2(BRK). Another event located in the same vicinity was the magnitude 5.5 ML(BRK) earthquake of September 5, 1955, located by BRK at latitude 37°22' N., longitude 121°47' W. While the magnitude of this event was less than that of the Morgan Hill earthquake and the felt area was only 43,000 km^2 as compared to 120,000 km^2, the isoseismal patterns are similiar.

Intensity Distribution

Figure 1 shows the distribution of intensities associated with the earthquake. Although the houses in the Jackson Oaks subdivision were constructed recently and satisfied the state and local building codes, some houses moved on their foundations, walls were shifted, decks were separated from their supports, and a chimney collapsed onto a roof. Many other homes in the Jackson Oaks area were damaged to a lesser extent. Some of the effects inside the homes were china closets, a heavy oak table, and a pool table were overturned; chairs appeared to have been flung around; and every drawer and cupboard was emptied onto the kitchen floor, with considerable breakage of china and glassware. One resident was thrown to the floor, and another was unable to get out of bed because the shaking was so strong.

Morgan Hill, Coyote, and San Martin (MM VII) suffered similiar types of damage which included cracked chimneys with some fallen, cracked brick walls; broken furniture; refrigerators moved, with some overturned; heavy industrial equipment knocked over; a large quantity of merchandise thrown from store shelves with considerable breakage; numerous store windows broken; and considerable damage to home furnishings. Some of the more significant effects were the roof on an old bank building in Morgan Hill collapsed, a heavy fork lift and a large truck loaded with lumber were observed to have been lifted off the ground in San Martin, and the United Technologies engineering building located south of San Jose was severely damaged and reported to have collapsed.

The isoseismals shown in figure 1 represent the generalized level of intensity for the affected area. However, some of the assigned intensities, particularly within the V and VI isoseismals, were anomalous.

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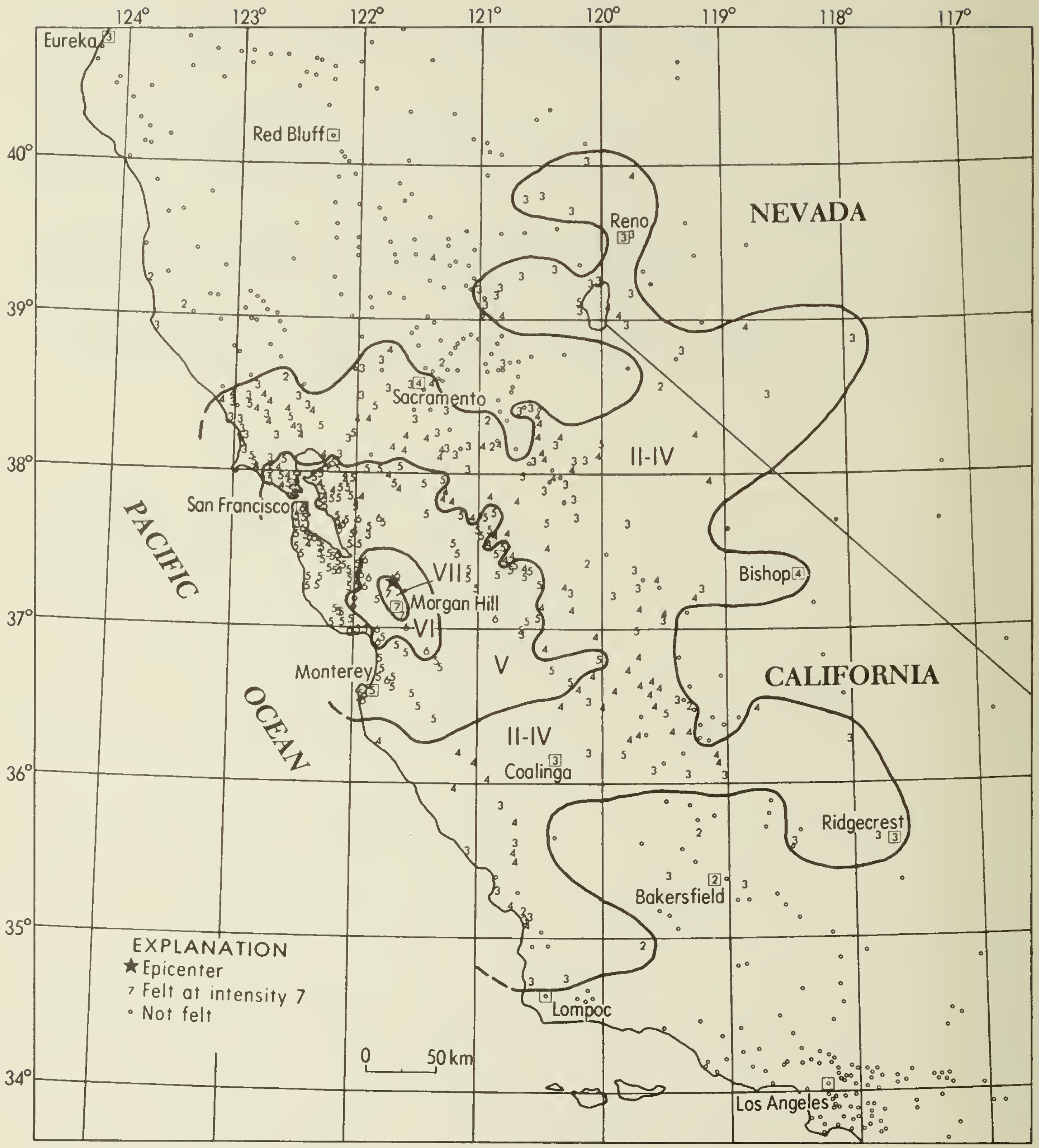

Figure 1.--Isoseismal map for the Morgan Hill, California, earthquake of April 24, 1984. Roman numerals represent Modified Mercalli intensity between isoseismals; Arabic numerals are used to represent the intensity at a specific site.

PERFORMANCE OF RESIDENTIAL STRUCTURES DURING THE MORGAN HILL EARTHQUAKE OF APRIL 24, 1984

by

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ABSTRACT

The Morgan Hill earthquake caused little structural damage. The population of Morgan Hill is approximately 19,000. According to the latest available data, there are 6,024 residences; of these, 834 are mobile homes. Less than one percent of the residential structures suffered major damage. Less than eight percent suffered minor damage. Damage to residential structures has been estimated by state officials to be $3,000,000.

INTRODUCTION

The investigation was conducted the day after the earthquake, April 25, 1984. The objective of the investigation was to locate and identify the damage to residential structures. Data collected was used to determine the reason for the damage. The damage was also compared to that of similar structures in past earthquakes to determine if anything new could be learned.

Observation of Damage - Single Family Dwelling

The majority of the damage occurred in the Jackson Oaks residential area east of Morgan Hill. Five homes in this area were condemned. These were the only homes condemned in Morgan Hill. The neighborhood is composed of recently constructed custom-designed homes overlooking the Anderson Reservoir. A peak horizontal ground acceleration of .63g was recorded at the Anderson Reservoir. This recording was taken approximately one mile from the Jackson Oaks area.

Two homes fell off their foundation, suffering partial collapse. These two homes, which were condemned, suffered cripple wall failures. If they had been properly engineered and the proper construction practices used, or if they had been strengthened before the earthquake, collapse could have been prevented. Both houses had been adequately anchored to the foundation (i.e., there were an adequate number of anchor bolts), and the sill plates remained in place.

[1]EBIS, Inc., San Francisco, California
[2]EQE, Inc., San Francisco, California

One of the homes mentioned above was a split-level structure with a short cripple wall under the single-story section. Homosote was used to sheath the cripple walls. Homosote is an insulating material normally used when there is no room to apply fiberglass insulation. The shear strength of this material is nominal. The other home mentioned above was a typical hillside structure with one story at street level and three stories in the rear. The entire house was sheathed with exterior plywood siding (T1-11). At the plywood panel joints, the sheets overlap each other to provide the appearance of continuity; only the top panels were nailed. These nails did not penetrate the plywood under the overlapping panel. The manufacturer calls for each panel to be nailed on all four sides. When the plywood panels were being attached to the top plate of the cripple wall, the nails were embedded between the bottom plate of the floor above and the top plate of the cripple wall. Effectively, only two sides of each plywood panel were nailed to the cripple wall.

Two-story homes with the garage acting as the first story performed in the expected manner. Exterior finishes cracked and some walls were displaced. Cracking in stucco and in concrete driveways was observed in several homes. Two masonry chimneys fell onto the roof, causing damage to the roof support systems and the interior. Many more masonry chimneys cracked or fell.

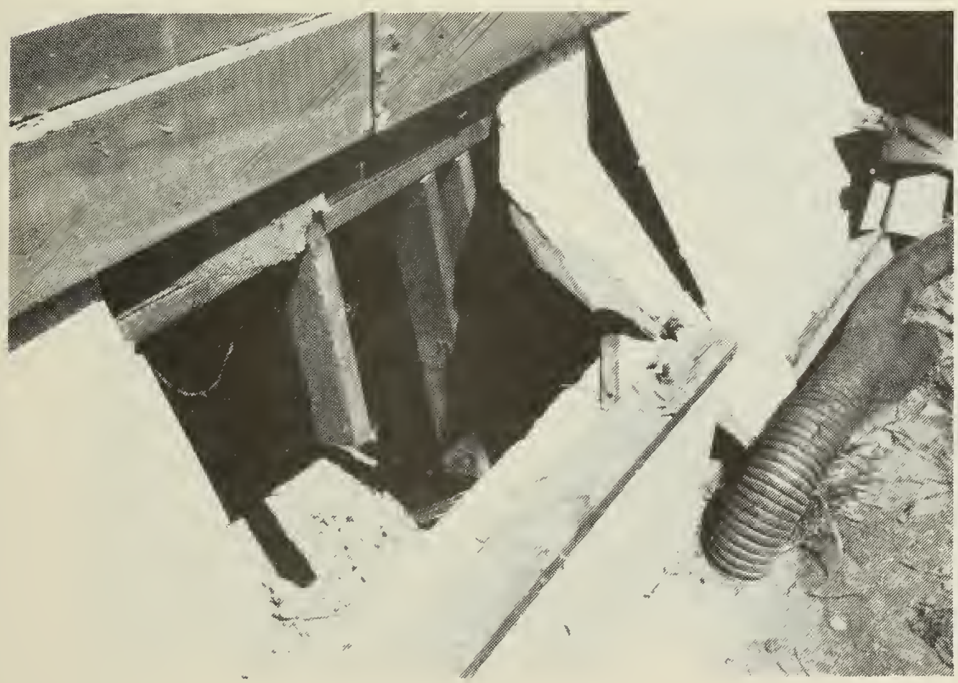
Reports vary on the number of mobile homes which were damaged. The number which were severely damaged ranges from 20 to 50. The mobile homes had no cross bracing and were resting on concrete blocks. This is typical of damage in past earthquakes.

Although most homes did not suffer structural or architectural damage, many homes in and around Morgan Hill had substantial interior damage. Large dressers and bookcases fell over, the contents of shelves in kitchens and other storage areas spilled onto the floor and pictures fell off walls. Short, squat pieces of furniture slid several inches in many homes. A few windows were also broken. The dollar loss attributed to contents by state officials exceeds $2.5 million dollars.

CONCLUSION

The amount of damage caused by the April 24th, Morgan Hill earthquake could have been reduced if proper construction procedures had been followed and inspection procedures more tightly controlled. If the building code requirement and the manufacturers specificaitons had been followed precisely, damage to structures could have been reduced 50% or more. The dollar loss attributed to contents was almost equal to the dollar loss attributed to structural damage. The protection of contents is a matter which each homeowner must handle. Securing the contents of a home is both simple and inexpensive. If the proper measures had been taken, losses to contents could have been reduced 75% or more.

Split-level home which suffered cripple wall failure due to the use of homosote as the sheathing material.



Close-up of split-level home.

Hillside home which suffered cripple wall failure due to inadequate nailing of plywood panels.

Close-up of hillside home.

Damage to two-story house with garage on first level.

Close-up of two-story house.

Failure of reinforced masonry chimney.

Collapse of mobile home.

Concrete piers which had fallen caused collapse of mobile home.

Interior damage to contents.

Interior damage to contents.

PERFORMANCE OF HIGH TECHNOLOGY INDUSTRIAL FACILITIES

by

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ABSTRACT

The Morgan Hill earthquake affected a large area of the southern San Francisco Bay area. There are many high technology facilities within the affected region. EQE engineers visited four representative facilities; their findings are presented here.

INTRODUCTION

The Morgan Hill, California, earthquake occurred on the Calaveras fault at 13:15 PST on April 24, 1984. The earthquake was reported as magnitude 6.2 on the Richter scale by the University of California Seismographic Station at Berkeley and magnitude 5.8 to 6.0 by the U.S. Geological Survey. The epicenter was at 37.317 N latitude and 121.680 W longitude, approximately 10 miles due east of San Jose. The earthquake hit hard enough to cause some plaster to fall and windows to break in buildings as far away as San Francisco.

The effects of the earthquake were relatively minor considering the proximity of the epicenter to San Jose, a large city in the greater San Francisco Bay area. The area shaken is populated by many high technology facilities. EQE engineers visited four representative high technology facilities close to the affected region; the findings are reported here.

UNITED TECHNOLOGIES CHEMICAL SYSTEMS PLANT

The United Technologies Chemical Systems Plant (CSD) is located on Metcalf Road in Shingle Valley, adjacent to the Calaveras Fault. The facility covers over 5200 acres and includes dozens of structures, mostly one-story steel and concrete tilt-up buildings. The facility dates back to the early 1960s; however, it was recently enlarged when all of the local CSD operations were centered there. The Calaveras fault crosses the eastern end of the CSD property, but the main complex is located about a mile west of the fault. The facility is located near the southern extremity of fault rupture of the April 24 event.

[1]EQE Incorporated, San Francisco, California

There were no ground acceleration records taken at the site. However, judging from the type and the extent of damage, it is apparent that the CSD facility was the most heavily shaken major industrial complex affected by the Morgan Hill earthquake. Ground accelerations at CSD probably exceeded 0.40g in the horizontal direction. Evidence to support this conclusion is observed in the number of items of rigid equipment which slid several inches during the earthquake.

The facility employs about 1200 personnel, most of whom were on the site at the time of the earthquake. There were no reported significant injuries. There were no reports of panic; employees seemed to be a little dazed following the earthquake. Personnel exited buildings once the ground shaking stopped. Most of this damage was cosmetic in nature - cracks in building facades and interior plaster, or fallen ceiling fixtures. Power was lost to the facility for several hours. CSD management estimated that about two days were required to bring the facility back to normal operation. Certain areas required more time, such as laboratories where instrument recalibration was required.

An itemization is provided below of the major damage in the facility as reported by CSD management.

Building

- In several cases steel buildings experienced stretched anchor bolts, popped screws in the steel siding, and buckled diagonal bracing.

- In several cases concrete tilt-up buildings experienced cracking of walls, broken weld connections, and at least one instance of a sprung wall panel.

- In most buildings damage was limited to cosmetic cracking rather than structural damage. Cosmetic damage was considered the greater repair cost compared to structural damage.

- Trailers which were used as temporary office facilities were knocked off their support jacks.

Building Internals

- Many cases of fallen ceiling panels were reported. The ceilings are suspended on T-bars with some diagonal wires in the suspension system. Most fallen panels were observed at ceiling-wall interfaces. It appears that the ceiling and wall rocked out of phase, creating differential displacement that tended to allowed acoustic panels to fall. Replacing suspended ceilings was a major source of business interruption.

- Acoustical ceiling fixtures such as lights were also reported to dislodge or fall. Several cases of fallen air conditioning ducting were reported. Generally, the fallen ducting was the flexible plastic type which does not present a significant hazard.

- Rod or chain suspended light fixtures in warehouses and shops fell.

- At least one case of fallen sheet metal ducting occurred. The fallen ducting impacted and damaged fire sprinkler piping.

- Roof-mounted air conditioners slid. The air conditioning units were restrained with wrap-around platic straps which did not have sufficient strength to resist the horizontal seismic loads.

- One large plate glass window slipped out of its frame and shattered upon impact with the floor. This was the only significant instance of window damage. The glass plate covered an exceptionally large area and it was thought that it may have been cut slightly short, so that the supporting frame did not adequately restrain it. The window was located on a stairwell between the first and second floors of the administration building.

- Laboratories lost a lot of glassware from shelves with subsequent breakage. There were no reported toxic spills.

- A large number of bookcases, shelves and filing cabinets toppled. At least one employee was bruised by a falling cabinet.

- Desk-top equipment slid to the floor. This caused damage to a number of typewriters and CRTs.

- The facility computer center was undamaged. Computer equipment is mounted on rollers which apparently absorbed the horizontal motion of the floor. The computer facility is mounted on a 12 inch raised floor, approximately 30 ft. x 50 ft. Floor pedestals are connected by stringers, but pedestals are not bolted to the floor.

Equipment

- CSD management indicated no problems wih electrical distribution equipment, except for a case of power lines disconnecting from power pole ceramic mounts. Transformers and switchgear apparently slid, but were undamaged.

- A portion of the facility is served by a set of large diesel-generators. These units came up as designed when power failed.

- CSD management could not recall any instances of instrumentation or control systems which were not operable following the earthquake (neglecting instrument recalibration).

- The facility includes 80 cranes and hoists, many of them large bridge cranes of the size found in power plants. The alignment of all cranes was checked following the earthquake and found to be correct.

- The facility includes a number of large shop intallations with heavy rigid lathes and presses. Many of these items slid several inches (an indication of strength of the ground motion). Re-alingment of this heavy equipment was a major recovery task.

- One cable tray failed. The cable tray was located at one of the outlying rocket test stands. The tray connected the control house with the test stand. The tray structure consisted of a series of single steel posts which supported three tiers of cable trays about eight to ten feet off the ground. The trays were cantilevered to the side of the posts. The steel posts failed near their base due to a lack of overturning resistance.

Tanks

There were apparently several instances of sliding tanks. Examples are included below.

- A tall vertical liquid oxygen tank sheared its anchor bolts and walked about 6 inches.

- Nitrogen bottles mounted horizontally in a steel rack sheared their welded connections to the rack and slid. Bottles did not rupture or fall from the rack. Some piping connections were torn.

- The facility includes its own water system, fed by large steel tanks located on hilltops. Tank sizes average about 200,000 gallons. The tanks are unanchored. They were reported to have moved on their foundations. There was at least one broken piping connection.

Piping

- Major piping damage occurred in underground lines. A total of 37 breaks were reported in buried lines. Pipe diameters range from 6 to 10 inches, buried at depths from 5 to 10 feet. Buried lines include transite pipe, cast iron, ductile iron, and mortar- or concrete-lined steel pipe. It appears that most breaks occurred in the cast iron or the concrete-lined steel pipe, primarily at connections.

- A few cases of pipe hanger failure were reported on fire sprinkler lines. In two or three cases, the sprinkler piping broke at couplings; these breaks seemed to be associated with hanger failure. It is apparent that above-ground piping damage was not widespread.
- There were no failures of high pressure lines other than one broken propane line which appeared to be associated with a sliding tank.

WILTRON FACILITY

Wiltron manufactures microwave communication equipment for telephone and other companies. The facility is located on Mast Street in Morgan Hill (photo 1), approximately 19 miles from the epicenter and four miles to the Calaveras fault. Wiltron leases the 15 year old reinforced concrete tilt-up building, which has a plywood diaphragm roof. The exterior dimensions of the one-story building are approximately 100x230 feet. The roof is supported with glu-lam girders, wood beams, and steel columns. The beams are supported by steel seats, and the beams and girders are positively anchored to the tilt-up walls. Although no estimate of site-specific ground motion is yet available, from the sliding of some unanchored heavy machinery and tables, we can estimate that it was between 0.3g to 0.4g (photo 2).

Ceiling tiles fell from the suspended ceiling at the perimeter walls (photo 3). The north-south running partition walls pulled away from the exterior tilt-up walls (photo 4). At the north side of the building, the wall separation varied from 0.5 to 1.5 inches. At the south side of the building, the partitions were crushed, resulting in approximately a 0.5 inch separation between walls. In one location, a lightweight metal stud buckled. The neoprene window glazing in some of the steel mullions popped out, probably because of the rotation of the glass in the window frame. There was some cracking in the roofing at the southwest corner of the building.

There were two circular ducting failures, and a few chain-suspended industrial light fixtures fell (photo 5). The suspended compressed-air lines showed no signs of leakage or damage. The plumbing remained intact, including the fire sprinkler piping system. Shelves in the storage area retained their contents. Solder sloshed out of an automatic solderer, splashing onto the nearby walls, ceiling, and floor.

There was no noticable structural damage to the facility. There were no cracks in the tilt-up walls and no separation of the roof diaphragm from the wall panels. A preliminary estimate for nonstructural damage of $20,000 is probably low.

ADAC CORPORATION FACILITY

The two-story ADAC Corporation building in Edenvale suffered some non-structural damage. The building is located approximately 6 miles from the epicenter of the earthquake and 5.5 miles from the Calaveras fault. It is a steel framed building with a metal deck roof and a concrete-filled metal deck second floor. The building was designed with a system of steel beams and joists supported by tubular steel columns. Vertical K-braces in both directions at both floors serve as the lateral load resisting system.

No damage was observed on the first floor; all braces, panels, and glass were damaged, and there was no evidence of yielding in the structural members. On the second floor, 15% to 20% of the ceiling tiles fell, probably because of a combination of whipping effects and diaphragm flexibility. More ceiling tiles fell at the perimeter of the building than in other parts. There was no damage to the K-braces at the second floor. A pane of glass that bends 90 degrees around a corner of the building cracked. Neighboring window panes shifted in their frames and another of the curved panes of glass shifted, leaving 1/4-inch gap between the glass and mullion.

INTERNATIONAL BUSINESS MACHINE, SANTA TERESA LABORATORY

Santa Teresa Laboratory is the computer programming development center for IBM's General Products Division. The laboratory is the first building to be specifically designed for computer programmers and the work they do. It is a 1200 acre facility located in San Jose, California, approximately 10 miles from the epicenter. It was reported that people could not stand during the strong motion. This included personnel on the ground floors as well as on the fourth floors of the towers.

IBM employs 2000 people at this facility. The facility totals about 585,000 square feet of floor space. Each of the eight Ductile Moment Resisting 4 story Steel Frame Towers are cruciform in plan with four wings. The towers are connected to the main circulation and service areas by a single story structure. The structures on the site are on an alluvial plane which varies from 40'-100' deep. The facility was designed for seismic loadings. The curtain wall panels are suspended at only two points to allow for racking as the building deflects. The piping through out the facility had been recently retrofitted with seismic bracings.

A set of strong-motion records were generated during the earthquake by the digital seismic data acquisition system at the facility. Data were recorded on 19 of the 22 installed channels of the system. The peak ground accelerations (PGA) recorded on the ground floor of the power house were: 0.21g N-S direction and 0.33g E-W, there was no vertical record available. The free-field PGA where: 0.25g N-S, 0.08g Vertical, and 0.48g E-W. There were recordings also available at three levels in tower D. These reported a PGA of: Penthouse (fourth floor), 0.54g N-S, 0.55g E-W; 2nd Floor, 0.49g N-S, 0.28g E-W; and 1st Floor, 0.41g N-S, 0.33g E-W.

There was no significant structural damage reported. A few suspended ceiling tiles did pop out, and there was some reported scraping at expansion joints between towers. There was no mechanical equipment damage with one exception that being a broken 2" plastic pipe buried in a patio area. The facility suffered no outside power loss, (even though there was some damage at the nearby Metcalf Substation).

CONCLUSIONS

The damage suffered by high technology industrial facilities reinforces the engineering profession's belief that buildings and their contents can be designed to withstand seismic forces. High technology facilities are very susceptable to equipment damage. As witnessed in the case of the CSD facility it was the equipment in the facility which suffered most of the damage and caused problems, not the structures themselves. In many instances at CSD and Wiltron, the repair of damage amounted to nothing more than realignment of equipment. However, this type of equipment damage can cause significant delays (2 days in the case of CSD) in resuming normal operations.

High technology facilities can learn from this earthquake that a little preventive seismic engineering can reduce the time required to recover from an earthquake. This time is very important in the fast moving competitive environment of high technology industries.

Photo 1. The Wiltron Mast Street facility in Morgan Hill shows no apparent signs of exterior damage. Nonstructural interior damage was extensive.

Photo 2. Many ceiling tiles fell in the Wiltron building.

Photo 3. Most interior partitions suffered significant damage at Wiltron.

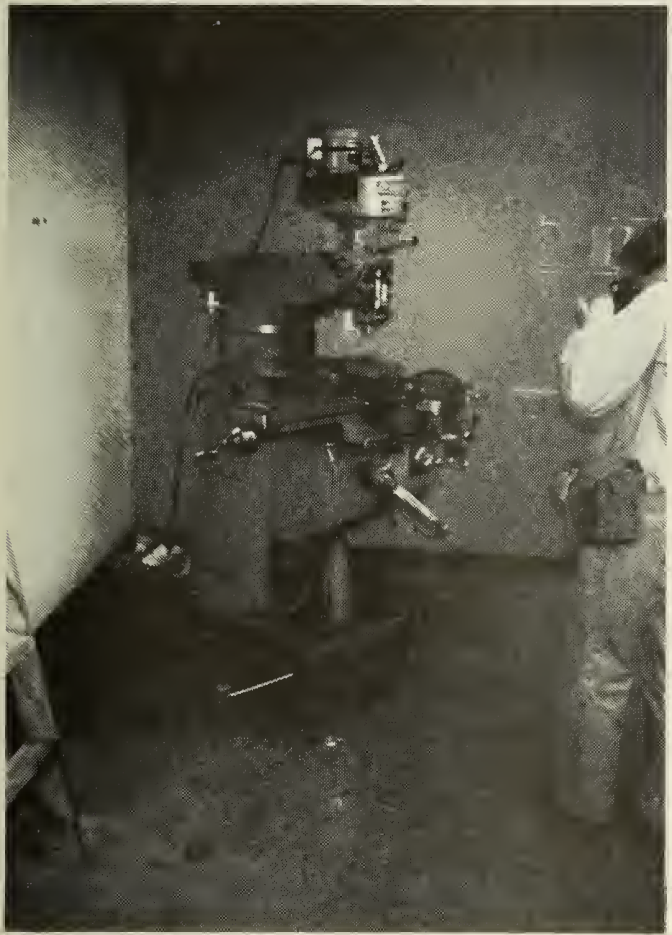

Photo 4. Shifting of heavy equipment at the Wiltron facility indicates a maximum acceleration at the site between 0.3g and 0.4g.

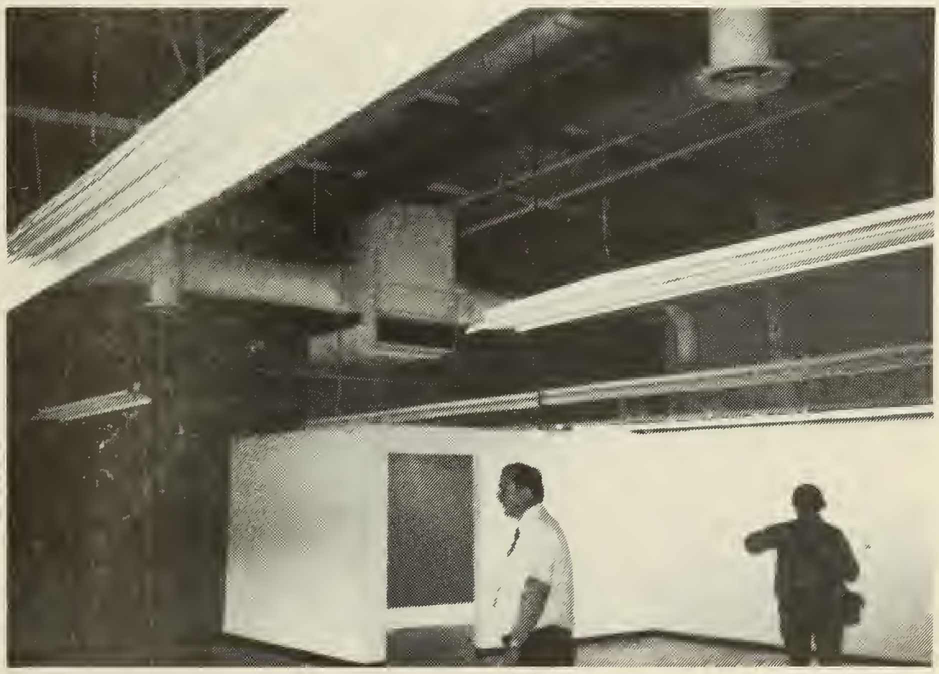

Photo 5. A few chain-suspended industrial light fixtures fell at Wiltron. There were also some circular ducting failures in this area.

EFFECTS OF THE MORGAN HILL EARTHQUAKE ON HOSPITAL AND PUBLIC SCHOOL BUILDINGS

by

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ABSTRACT

Hospitals constructed under the provisions of the Hospital Act and public school buildings constructed under the provisions of the Field Act performed quite well during the Morgan Hill earthquake.

INTRODUCTION

Shortly after the 6.2 M Morgan Hill, California earthquake at 13:15:19 PST on April 24, 1984, representatives of the State of California visited various hospital and public school sites in Morgan Hill, San Martin, Gilroy and San Jose. The purpose of the visits was to determine the extent of the damage with a view of reviewing adopted procedures and regulations relative to hospital and public school construction.

PERFORMANCE OF BUILDINGS

The following describes the observations made at each site.

Hospitals

Wheeler Hospital, Gilroy

This site contains buildings constructed both prior to and after the enactment of the Hospital Act. A $2.8 million project for a new addition of structural steel framing with reinforced walls and additions and alterations to the existing building was completed in 1980. There was no structural or nonstructural damage of any kind to this facility.

Alexian Hospital, San Jose

This site contains a five story, a two story and a one story reinforced concrete shear wall building with post tension horizontal framing. These buildings were constructed in 1963, prior to the enactment of the Hospital Act. Damage occurred to the finish materials at the seismic separation joints, some light cracking was produced in the shear walls and in the non-structural walls and a piece of equipment overturned.

1 Principal Structural Engineer/Research Director, Office of the State Architect, Structural Safety Section, Department of General Services

The $15 million additions constructed in 1974 and 1982, under the provisions of the Hospital Act, had no damage to the structure or any equipment. Some hair-line cracks occurred in nonstructural partitions. The 1974 addition is of one story reinforced concrete shear construction. The 1982 additions have a partial basement and one story ductile moment frame designed for a future second floor.

Schools

Jackson Elementary School, Morgan Hill

The buildings on this site, built in 1978, are one story essentially circular buildings with reinforced concrete abutments aud laminated timber roof beams, roof beams placed radially. The remaining framing is of wood with plywood roof diaphragms.

No structural damage was noted. Lay-in ceilings were damaged in areas of several rooms. The ceiling panels and T-bars became dislodged and fell to the floor. It was reported that the end of a T-bar penetrated the seat of a folding table in the cafeteria of sufficient depth to hold the T-bar in an upright position. Several ceiling grilles fell out of the plane of the ceiling. The ceiling was not installed in accordance with the approved drawings. It was suggested to the school district superintendent that the contractor be required to correct the deficiencies.

Morgan Hill Elementary School, Morgan Hill

It was reported that this original wood frame public school was constructed in 1922. As evidenced by steel framing around the outside of the building, the original building was strengthened after it was constructed. Work was done on the site in 1933, 1934 and 1945; however the file documents for the correction work on these projects are not available.

Plaster cracks were observed throughout the buildings; however due to the age of the structure the cracks appeared to have existed prior to the earthquake. Two steam radiators fell off the walls. A small amount of damage occurred to the recently installed unbraced ceiling and light fixtures in the multi-use room.

Britton Middle School, Morgan Hill

The auditorium at this site, constructed in 1975, is of one story reinforced concrete wall construction with steel roof trusses, steel cross bracing, wood joists and square sheathing over the seating area. The proscenium wall and stage roof is of concrete construction.

Cracks were observed in the concrete wall near the stage at the southwest corner of the building. These cracks were present before the earthquake and

were accentuated by the earthquake. There are cracks in the stocco in need of repair. A few accoustical ceiling tile that had been glued to the plaster ceiling fell.

No significant damage was noted.

It was suggested to the school district superintendent that a structural engineer examine the cracks in the proscenium wall and the cracked stucco and make recommendations for their repair.

San Martin Elementary School, San Martin

The buildings on this site consisted of six wings and kindergarten of typical wood truss, wood frame and plywood sheathed buildings. The site also contained a multi-use building of wood frame construction with glue-laminated wood timbers and plywood sheathing. Buildings on this site were constructed in 1952, 1956 and 1964.

No damage was noted.

Raymond Gwinn Elementary School, San Martin

This site contains two rectangular buildings, built in 1978, of concrete block exterior walls, wood framing, glue-laminated wood timbers and plywood sheathing. No structural damage was noted.

Several book shelves placed next to walls overturned. One of the overturned book shelves, 6 feet high and 15 feet long, was connected to the wall with 4" x 4" x 1/8" x 7/8" long steel angles at about 3 feet on centers. The connection to the wall was with screws into the gypsum board interior finish rather than a solid backing material. Another book shelf about 6 feet high and 4 feet wide overturned on a student while she was in the "duck and cover" position. That is, she was partly under her desk and the book case, filled with paperbacks, fell on her back. No injuries to this student were found at the hospital.

A piece of student art work consisting of a thin layer of plaster on a piece of ¼" plywood about 14" x 18" fell on a student while in the "duck and cover" position. No injuries to this student was found at the hospital.

South Valley Junior High School, Gilroy

The classroom buildings on this site are one story wood frame construction placed in a finger type arrangement. The buildings on this site were constructed in the 1960's.

No structural damage was noted. Florescent light tube fixtures fell in several classrooms. No injuries occurred. The fixtures were hung from the ceiling with steel wire cables. The cable anchorages were made with a device

pressed on the ends of the cable. All of the failures occurred at the lower end of the cable when the pressed device slipped free, thus allowing the fixture to fall.

It was recommended to the district superintendent that the remaining light fixture hangers be tested and corrected as appropriate.

CONCLUSIONS

The type of damage found at the hospital and public school buildings disclosed that the adopted regulations appear to be adequate, however they must be followed in the field. The ceiling and light fixture damage disclosed that the field control of these items must be improved. Also building owners and their staff must become aware of the importance of properly anchoring fixed shelving, equipment, etc. which are installed by the owners.

ACKNOWLEDGEMENTS

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MORGAN HILL EARTHQUAKE INVESTIGATION OF LIFELINES

Anshel J. Schiff[1]

ABSTRACT

The overall response of all lifelines was good although there was some significant damage. In the power system, there was significant damage to 500-kv circuit breakers at two substations, some other minor substation damage, and some damage to feeders in the distribution system. The substation damage did put a segment of one of the AC Pacific Interties out of service for a couple of days, but the remaining intertie was able to carry the total load. The loss of feeder lines caused local disruption of power for up to five hours. In water and sewage systems, two 8" transite water lines broke in Morgan Hill, and a break in an 8" pipe to a 350,000g tank caused a large water loss. Five 6" water line couplings disengaged. There appeared to be no other damage to the water or sewage systems although post-earthquake seepage rates had not been determined. In communications systems, there was no significant damage, but there was a significant downgrade in the quality of service due to system overload. Calls from outside the area were limited by AT&T. In highway systems, damage was limited to that caused by a rock slide that blocked E. Dunne Avenue near Anderson Lake and damaged a nearby bridge over the lake. One bridge span moved one foot near an abutment and caused the adjacent pier to move out-of-plumb by almost one foot. The road surface on the crest of Anderson Dam was cracked, but there was no damage to the dam. In the natural gas system, there was no damage to the utilities part of the system. A large fire in San Jose was caused by a gas leak in piping to a gas-fired industrial heater. There was an explosion and fire in a mobile home and numerous gas leaks associated with toppled water heaters. There were numerous leaks to service connections to homes in the high-damage area.

INTRODUCTION

The following report describes the effects on lifelines of the Morgan Hill earthquake of April 24, 1984. The investigation was done under the auspices of the Earthquake Investigations Committee, TCLEE, ASCE. Others contacted to see if all observed damage was reported included Sam Swan, Gordon Laverty, Dave Miller, and Tom Chan from EQE, Inc. James Gates, CALTRANS, provided information on highways, and George Lenfestey, P.G. & E., provided information on power and gas systems. The investigation was also coordinated with Gordon Dean who was in charge of the EERI investigation.

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POWER SYSTEMS

While the overall performance of the power system as measured by customer disruption was good, the most significant damage to any of the lifelines was to the power system equipment. Most of the damage occurred at two transmission substations with additional damage at a distribution substation and minor problems in the distribution system.

Los Banos Transmission Substation

The Los Banos substation is located just south of State Route 152, on the west side of Interstate 5, just outside of Los Banos. It is about 80 miles east by southeast of the epicenter and about 30 miles from the nearest fracture zone. Several people who were at the site at the time of the earthquake were interviewed. While all recollections were not consistent, it would appear that there was an initial brief, low-frequency, wave-like motion followed by a larger amplitude, longer duration, wave-like motion. There was a few seconds gap between the first and second motions. There was sufficient time for one individual just outside of the substation control room building to enter the building and start to announce the earthquake. An operator inside the building who had not felt the first motion looked up and out of the front door, which faces north, to see what appeared to be approaching waves. The station floor followed the wave motion which was estimated to be between 3" to 6" crest to trough. There was no estimate for the wave length. Control cabinets seemed to rock back and forth with the waving floor motion rather than in a vibrational mode. One individual working at a terminal and sitting on a chair with casters noted a relative peak-to-peak, horizontal motion of about 8" to 12" between his hands and the keyboard. There was no damage in the control room, and nothing on the desks tipped over or fell to the floor. All of the descriptions of the ground motion used terms like "rolling" or "wave-like" motion, rather than vibration, to describe the earthquake. Damage to the 500-kv circuit breakers (CBs), which was accompanied by loud noise, occurred shortly after the arrival of the second series of ground motions.

It is interesting to note that a small grocery store located at the entrance to the substation access road and about 2,000 feet from the substation had almost nothing fall from its shelves. Also, small post-insulators which were stacked on a pallet two high and were relatively unstable did not fall over. Thus, it would appear that the motion at this site was low-frequency in character and had low accelerations associated with it. There were several strong-motion instruments in the vicinity of the substation. One instrument northeast of Los Banos, about ten miles from the substation and the same distance from the epicenter as the substation, recorded a peak acceleration of .06g horizontal and .01g vertical. At the foot of San Luis Dam, several miles west of the substation, the peak accelerations were .04g horizontal and .01g vertical.

Higher accelerations were recorded on the crest of the dam and on debris catchers associated with the dam. These acceleration values are initial estimates obtained from the records.

The area surrounding the substation consists of rolling hills, but most of the site appears to be built on cut rather than filled surface. The filled part of the site (southeast corner) does not have any equipment on it. Figure 1 shows the overall layout of the site. A cursory review of the site indicated no signs of distress such as cracked paint, soil compaction around foundations or footings, or cracks in the soil, except as noted below. Items A and B are banks of 500-kv circuit breakers which suffered most of the significant damage. Item C is a slightly distressed frame-mounted 70-kv oil circuit breaker. Item D is a bank of circuit breakers similar to those at A but were not damaged. Item E indicates the position of stored post-insulators that were unperturbed by the earthquake.

The circuit diagram for the 500-kv switchyard (Figure 2) depicts the use of the breaker-and-a-half scheme for protecting the lines between Los Banos and interconnecting points. The heavy lines show the connections that can carry power with the damaged CB out of service. Note that a single line represents three physical lines, one associated with each phase. Figure 3 is a schematic diagram that indicates the position of the current transformer (CT) relative to the three individual interrupter heads for each of the live tank CBs. This would represent the CBs contained in Box A in Figure 1. The interconnections, bus, and air disconnect switches are not shown in the figure.

Figure 4 shows an overall view of undamaged live tank CBs with the CT on a separate stand at the end of the CBs. Two CBs of this type had damage to the large porcelain members which support the interrupter head. On one unit (a, in Figure 3), two of the four support members shattered, leaving the interrupter head supported by the link which connects it to the CT, the interconnection to the adjacent interrupter head and the tendons contained in the column. Figure 5 shows an undamaged connection between the CT and the CB with provision for limited relative motion between the units. The link on the damaged CB was bent from supporting the weight of the interrupter head after the support column failed. Figure 6 shows the damaged circuit breaker after the interrupter head has been removed. The six wooden tension rods used to hold the interrupter head to the base of the CB and the control rod were sawed off when the interrupter head was removed. Figure 7 shows the interrupter head after it was disconnected from the rest of the CB. After the porcelain fractures, the insulating gas, which it contained under pressure, escapes. After the earthquake, the CB was in the closed (original) position. Opening of the CB after the loss of insulating gas would cause internal arcing and may weld the CB in a closed position. There are interlocks to prevent this from occurring. The circuit must be de-energized by using a CB elsewhere in the circuit.

The second CB (b, in Figure 3), with a damaged vertical column, had the lowest of the four members cracked. Figure 8 shows the unit after it had been removed. A small wedge of porcelain was chipped out near the bottom of the column. The crack extends over the entire length of the lowest member although it is not clearly visible in the picture.

The other type of damage to these CBs was the failure of the diagonal braces used to restrain the columns for wind loads. Each column had two braces. Each brace is rigid so that it can take both tension and compression, although compression loads would be limited by buckling instability. A total of "twelve" braces on five CBs broke; their position on the various units is designated by a dot at the end of the brace shown in Figure 3. Most members failed at the sand ring, i.e., the region near where the porcelain is joined to the end mounting flange. An example of failed braces is shown in Figure 9. Figure 10 shows a schematic of a brace assembly made up of five porcelain members. Most failures occurred at position A or B with one failure at position C and D. The ends of the braces are rigidly supported. Since porcelain members often fail at the sand ring as this appears to be weak point, and the alignment of the end supports prior to assembly would significantly effect the initial distribution of stress in the brace, it is difficult to identify the failure mode with much confidence. It is interesting to note that only one brace failed on any single column except for the column that had shattered its support column, where both braces failed. The cracked column had both its braces intact. There were no other signs of distress on the CB.

Figure 11 shows a picture of the CT mounting and its support stand. The CT is supported on four 5" channels forming a pattern similar to that shown in Figure 3. On many of the connections between the 5" channel (attached to the base of the CT and extending under it) and the CT support stand, cracked paint indicated that there was severe loading. The locations of these signs of distress are indicated by small dots in Figure 3. The rather irregular pattern may be explained by variations in the tightness of bolts which secure the channel to the CT stand. There were no signs of distress in the clips which hold the CT support stand to its foundation pad. Figure 12 shows the support stand used for the CTs on the other transmission circuit (D on Figure 1) in which no cracking of paint was observed, and the CBs were undamaged. A rough estimate of the natural frequency of the CT is 2.5 Hz, although a more realistic value is probably below 2 Hz. It is suggested that the CT may have been excited by the low-frequency ground motions, and the stiff connections, with limited play between the CB and CT, transferred load to the CB causing its failure. Supporting evidence would be that the more rigid CT supports shown in Figure 12 raised its frequency so that there was less interaction with the ground motion and less deflection. Also, all interrupter heads with damaged columns (this is also true for the Metcalf substation discussed below) were immediately adjacent to the CT. Not all evidence supports this conclusion. First, if there was vibration of the CT, why wasn't the paint cracked on both sides of the CT support rather than the rather irregular pattern observed? Also, how does one explain the failure of diagonal braces on interrupter columns not adjacent to the CT,

particularly, when in some cases, the intervening columns and associated braces were not damaged?

Another live tank CB by a different manufacturer also failed. Its position is indicated by Box B in Figure 1. These CBs have four interrupter-unit support columns, each supported by three diagonal braces. The braces also have intermediate braces to the main column. Each column supports two interrupter heads together with pre-insertion resistors and grading capacitors. An aluminum casting which connects the interrupter head assembly at the top of one column failed. Figure 13 shows the column without its interrupter head. The supports connecting the mid-point of the column to that of the diagonal brace can also be seen. Figure 14 shows the underside of the interrupter head with its fractured support. Figure 15 shows the bottom half of the failed head support.

Utility personnel reported that legs of several frame-mounted 70-kv CBs also showed minor signs of distress due to lack of adequate diagonal bracing. The author could not locate these items. There were 500-kv live tank CBs of another manufacturer at the site that were undamaged.

Metcalf Substation

The Metcalf Substation is located near the intersection of U.S. Highway 101 and Metcalf Road. It is located about ten miles southwest of the epicenter and about four miles from the nearest fault rupture zone. Strong-motion records were obtained on each side of the substation on a line bearing northwest by southeast and about ten miles away. The record obtained northwest of the site at the U.S. Highway 101 and Interstate 280 overpass had peak accelerations of .12g horizontal and .08g vertical. The other record obtained southeast of the site had peak accelerations of .20g horizontal and .41g vertical. The site appears to be located on flat, ungraded ground. An interview with personnel at the site who were there during the earthquake indicated that there were three phases to the earthquake motion. The recollection was that, first, there was a rolling motion, followed by a vibration, which was followed by a vertical vibration, although the order of the motions may have been different. Nothing in the control room tipped over nor fell. One individual felt what appeared to be a swaying motion from his position under his desk.

The major damage was to a live tank 500-kv CB. The CBs at this site are modified, earthquake-resistant versions of those at the Los Banos site. Figure 16 shows the damaged CB which is missing one interrupter head and support column. The absence of diagonal wind braces in these

internally strengthened units and a CT on its support stand of the same design that showed distress at Los Banos are also shown. Figure 17 shows ten fiberglass tendons used to pre-tension the interrupter-head support columns in this strengthened CB, as compared to six wooden tendons seen at Los Banos. Three of the four porcelain members of the column failed with some violence as some porcelain fragments were found some distance from the CB. Of the 36 columns at the site, only one failed. Again, the damaged column was adjacent to the CT which has the same support structure design that showed distress at Los Banos. Unlike Los Banos, many of the clamps which secure the CBs to their foundations showed varying degrees of distress. One clamp, in which the nut was only partially engaged on the stud because the stud was short, limited its load restraining ability. Figure 18 shows how another hold-down bolt has been stretched about 3/16" with a ruler placed in the gap. In some cases, there was slight horizontal motion of the CB support legs, the maximum being about 7/16". Figure 19 shows the layout of the CBs at the site. The rectangles represent the CBs, and the dots distributed around each indicates if the hold-down clamp showed any signs of distress as demonstrated by cracked paint. It should be noted that the loads on the hold--down bolts will experience from two to three times the vertical load applied to restrain the CB. It would be interesting to investigate the exact nature of the apparent stretching of the bolts as this may provide some indication of the force that was applied to the CB. Clearly, the magnitude of the shaking at this site was more severe than at Los Banos.

As at Los Banos, the CT support stands show signs of severe loading by the presence of cracked paint. Dots show distress joints on Figure 19. The only CT support structure hold-down clip to show distress was the one adjacent to the damaged CB. There was no indication of relative motion between base slabs or footings and the surrounding ground.

The only other failure at the site was a lightning arrestor (Figure 20) mounted on a 230-kv transformer. Figure 21 shows a line of seven transformers. The new lightning arrestor (vertical member in center of picture) replaced the damaged lightning arrestor shown in the foreground. Interestingly, three other identical units and three similar units adjacent to the failed unit were undamaged. This is indicative of the large dispersion in strengths associated with porcelain members.

At the transmission level, no trip-outs were caused by the interaction of the seismicly induced sloshing of transformer oil and the sudden pressure relays.

Edenvale Substation

The Edenvale Substation is located near the intersection of U.S. Highway 101 and State Route 82 and about three miles northwest of the Metcalf Substation. This would place it about seven miles away from a site with peak accelerations of .12g horizontal and .08g vertical. A flag on a tripped relay indicated that it was caused by the activation of the sudden pressure relay in the transformer. A repair crew was dispatched to the site and reset the CB.

Distribution System Problems

The service center which dispatched repair crews in the Morgan Hill area had 30 service calls. The distribution voltage in the area is primarily 12 kv and 21 kv with very little 4 kv. Of the 30 service calls, ten were for distribution line burn-down; i.e., the wires associated with two phases of a circuit are set into motion by the earthquake, come in contact with each other, and burn through the line causing it to drop to the ground. The fallen line may remain energized. There were no cases reported of lines becoming wrapped together. There appeared to be a few cases of transformer failure, although none were reported to have fallen from their support structure. Some fuses on tap lines had to be replaced. Two underground cable problems were reported. One had a bad cable, indicating that there was a 4-amp flow. Another cable checked out after test voltages were applied to it. There is a significant amount of underground cable in most of the new residential areas, and these had no problems. The extent of ground failures in the region is not known. On many of the service reports, lines checked out after test voltages were applied.

In discussions with telephone companies, it was learned that one telephone substation was without normal power until 4 p.m., and another did not have service restored until 6:15 p.m.

System Performance

At the transmission level, the loss of CBs at Los Banos did incapacitate the Los Banos-Midway No. 2 Intertie lines as well as service to the 500/230-kv tranformer banks. While the capacity of the operational line could carry the pre-earthquake load, bus limitations caused by the loss of three CBs on the three 500-kv lines did limit the flow of power that could be put out over the operational tie line. Two days after the earthquake, the CB with the cracked support column supplying the 500/230-transformer bank had its entire column replaced with a spare, and final adjustments were being made to place it back in service on April 26. All

of the failed diagonal braces had been replaced with spares that had been brought to the site. A replacement column for the shattered column had been brought to the site, and service to the Los Banos-Midway Line was restored on April 30.

At Metcalf, the failed CB stayed in its closed, pre-earthquake position. Two line breakers tripped and were reclosed without disruption as they have high-speed reclose (3-cycle) capability. The damaged lightning arrestor at Metcalf had been replaced with one from a spare transformer at the site. It was not known how long it would take to replace the damaged 500-kv CB.

At the distribution level, the requests for service were responded to shortly after they were received with service being restored by evening. In some cases, service calls were not received until the following morning as people who left work following the earthquake did not find problems until the next morning when they returned to work.

As to power system communications, there was no disruption to the microwave systems which connect all 500-kv stations. There was disruption in telephone company lines, but this did not cause any problems.

COMMUNICATIONS

Three different telephone companies service the area of shaking. San Martin is serviced by Pacific Bell, Morgan Hill by General Telephone, and Gilroy by Continental Telephone. The only damage that was reported was fallen ceiling tiles at several facilities. Power was disrupted to several facilities and was not restored until 4 p.m. in one case and 6:15 p.m. in another. Emergency batteries were used to start motor-generator sets which provided operating power until utility service was restored.

There was extensive disruption to service in the area due to high traffic-flow conditions. Dial tone delays could be 30 seconds or longer. Many individuals assumed that there was no service if they did not wait long enough to get a dial tone. While this could discourage users and reduce system load, efforts to make critical calls could also be abandoned. Because of the large influx of calls, AT&T activated system-control procedures to limit the volume of incoming calls. This was done to free up circuits to allow local people to get out and to communicate in the local area. It should be noted that when traffic is limited, external calls do not have priority other than some special telephone company lines. Internal traffic was still very high two days after the earthquake. The overload problems emphasize the need for intensified public education.

WATER AND SEWAGE SYSTEM

Water system damage was limited to the Morgan Hill area. Most damage was to transite pipe and its couplings. There was one transverse break in an 8" pipe section and one in an 8" pipe coupling. In the Oakridge Court and Lane area, where most houses were damaged, five 6" pipes had their rubber-seal type fittings pulled apart. In Jackson Oaks, a 350,000g tank had the threaded part of an 8" steel pipe break where it connects to a flange. The 28'-high tank was nearly full and lost about 10' of water before the pipe was repaired. This took about three hours. Due to one of the 8"-pipe breaks, about half of the Holiday Lake service area, or about 500 to 600 homes, were without water. Most service was restored by 8 p.m. Four of ten wells which provide water to the community were out of operation due to the loss of electric power. Manual reset is required after power has been restored. About a week after the quake, one plastic pipe to a meter was found to be leaking and was repaired. Checks for contamination of the water system showed it to be safe.

No damage to the sewer system was observed; however, the system does not have a method for monitoring leakage. As sewer systems are usually less robust than the water system, some damage can be expected. Typically, sewer damage takes several months to exhibit itself when broken pipes become clogged.

A local plumber was contacted to evaluate damage beyond the service connection, which is the responsibility of the home owner. The damage reported is estimated to represent about one-fourth of that experienced in the area. For some three hours after the earthquake, three men were in the area responding to calls to shut off water and gas service due to leaks beyond the service connection. In the three weeks after the earthquake, there were nine repairs to PCV pipe damaged from shifting soil. At three locations where pipe penetrated a concrete surface, as entry to a basement, the pipes sheared, independent of pipe material. Some 21 to 25 water heaters were replaced when legs failed and they tipped over, often damaging water-line connections. None of the damaged water heaters had seismic bracing nor restraint straps. New heaters are installed with straps. Damage is still being reported, primarily to lawn sprinkler systems. It is anticipated that additional water leaks will be reported on intermittently used lines, such as showers, after time is allowed for water to saturate wallboard. No damage to homeowner sewer lines has been reported, but this often takes time to exhibit itself through seepage and blockage associated with cracked pipes.

There appeared to be no other damage to water or sewer systems in San Jose or Gilroy.

A roadway on the crest of the earthfill Anderson Dam cracked. The dam was inspected and declared safe.

HIGHWAYS

A bridge near the Anderson Dam which provides access to a local park was damaged by ground instability. No other significant roadway damage was reported.

GAS SYSTEM

There was no reported damage to the gas transmission or distribution system. There were several problems beyond the service connections. A large fire in a San Jose shopping center was started when a gas-fired parts cleaner developed a leak at a union. Leaking gas collected in a confined area and started the fire when the heating unit cycled on about 15 minutes after the quake.

In Morgan Hill, there was an explosion and fire in one house trailer. In the area where there was damage to homes, local plumbers, Pacific Gas and Electric, and fire department personnel shut off gas service where gas leaks were located. One plumber reported that three or four service connections outside the house broke as well as twelve gas leaks associated with toppled water heaters. Also, leaks developed in five fireplaces. In four of these cases, service to the entire house had to be shut off since the fireplace did not have a separate shut-off. As the gas leaks were in pipe within the masonry work, repairs would be timeconsuming and costly.

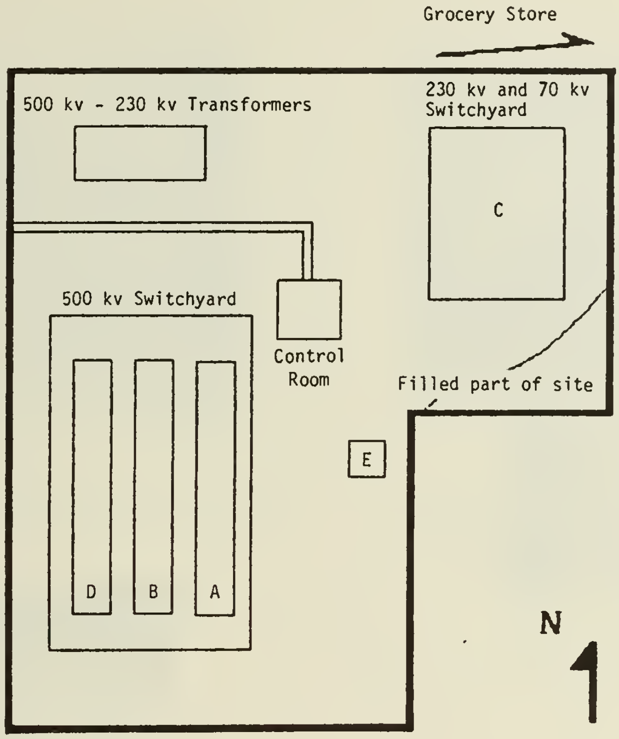

Figure 1. Los Banos Substation Site Layout (not to scale).

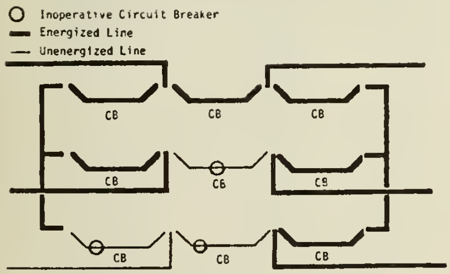

Figure 2. Circuit Diagram for 500 kv Los Banos Switchyard.

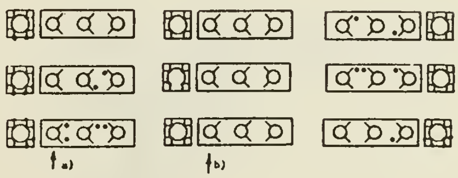

Figure 3. Schematic Diagram of Damaged CBs at Los Banos.

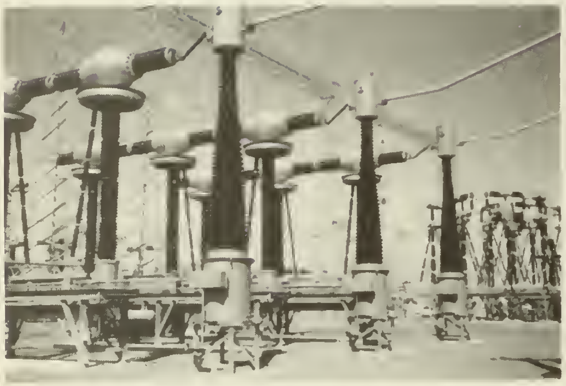

Figure 4. Live Tank Circuit Breaker.

Figure 6. Damaged Live Tank Circuit Breaker.

Figure 5. Circuit Breaker-Current Transformer Undamaged Connection.

Figure 7. Interrupter Head of Live Tank Circuit Breaker.

Figure 8. Cracked Interrupter Head Support Column.

Figure 9. Two Damaged Stays.

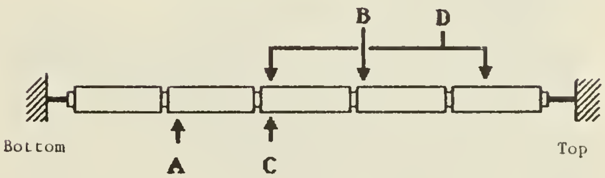

Figure 10. Schematic Diagram of Column Brace.

Figure 11. Current Transformer Mounting and Support Stand.

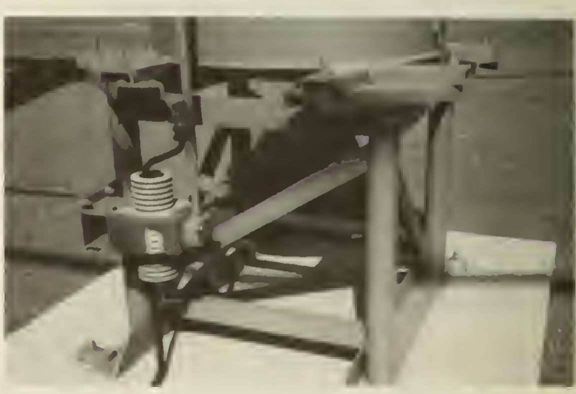

Figure 12. Current Transformer Support Stand Near Undamaged CB.

Figure 13. Support Column Without Interrupter Head.

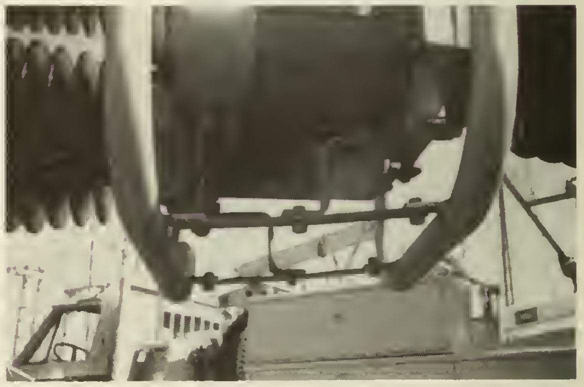

Figure 14. View of Bottom of Interrupter Head.

Figure 15. Bottom Half of Damaged Head Support.

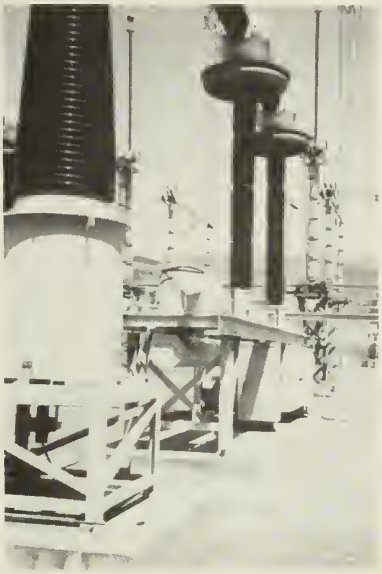

Figure 16. Damaged Circuit Breaker at Metcalf.

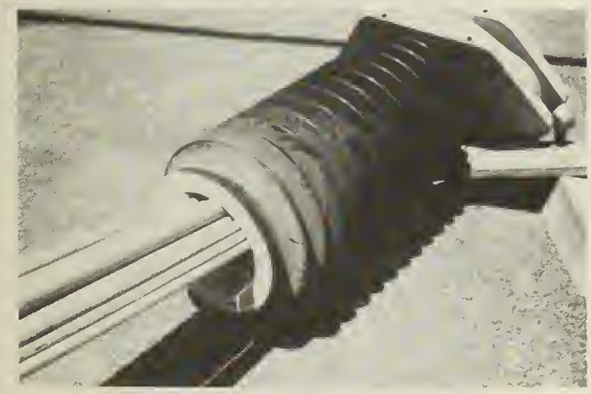

Figure 17. Remains of Column Showing Internal Tendons.

Figure 18. Stretched Hold-Down Clip Stud.

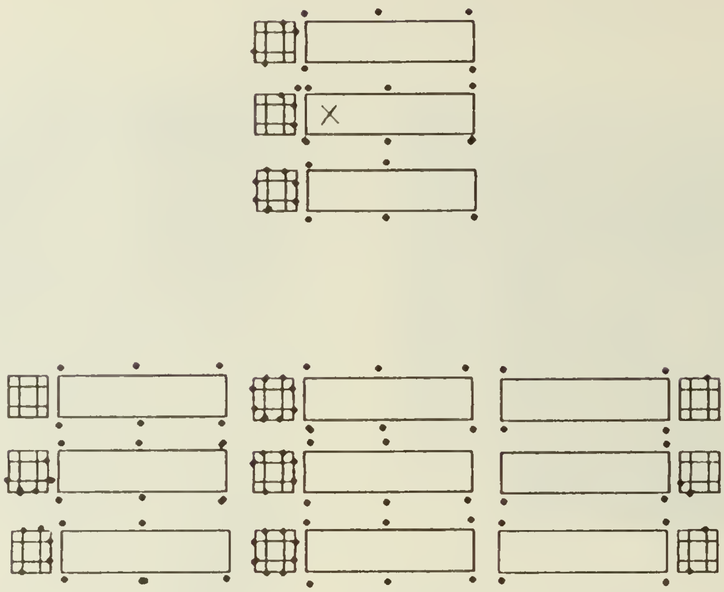

Figure 19. Location of Stressed Points on CBs and CTs at Metcalf Station.

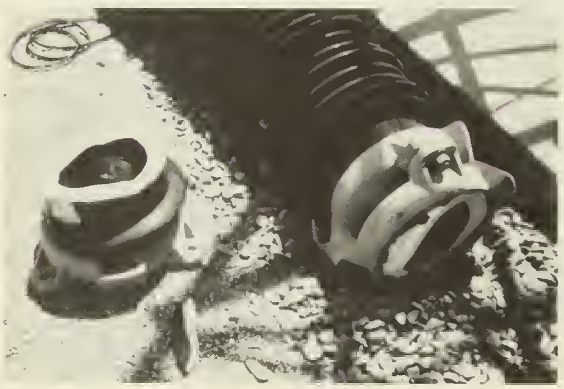

Figure 20. Fractured Lower End of Lightning Arrestor.

Figure 21. Repaired Lightning Arrestor and Transformer Bank.

RESPONSE TO THE MORGAN HILL EARTHQUAKE AND OBSERVATIONS BY THE STATE DIVISION OF SAFETY OF DAMS

by

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William J. Bennett[2]

Introduction

The responsibility of the Division of Safety of Dams (DSOD), California Department of Water Resources (DWR), is to protect the public against failure of dams and reservoirs. Division 3 of the California Water Code grants DWR the power to supervise, with regard to safety, the construction, enlargement, alteration, repair, maintenance, and operation of dams and reservoirs. The Code also gives DWR the power and the responsibility to employ any remedial measures necessary to protect life and property. The size of dams under the jurisdiction of the State of California is shown in Figure 1.

Any earthquake within California or adjacent to its borders, of magnitude 5 or greater is reported to personnel of the DSOD Geology Branch on a 24 hour basis. During normal working hours these reports are made by the DWR Earthquake Engineering section, after hours by the State Water Project Operation Control Center. A hazard assessment is made immediately, the appropriate regional engineer of the DSOD Field Engineering Branch is notified, and necessary action is taken. The Morgan Hill earthquake of April 24, 1984 prompted the following response and observations by DSOD.

Response

DSOD was first alerted to the quake at 1315 hours by its "early warning" earthquake board which is connected to 15 sensitive seismographs statewide. Within a few minutes DSOD staff determined that an earthquake of about magnitude 6 had occured in the South Bay-Hollister area. Within one-half hour the DWR Earthquake Engineering Section provided a preliminary location (longitude and latitude coordinates) and a preliminary magnitude.

According to DSOD procedures, all dams which have experienced an estimated peak bedrock acceleration of 0.05g or more during any earthquake in California are to be investigated. The

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intensity of ground shaking is estimated by earthquake magnitude and the Seed and Idriss, 1982, attenuation curves. The area of investigation for a magnitude 6 2 earthquake is a circle with a 40 mile radius measured from the earthquake epicenter. This area is subject to change as more accurate information is received.

Using the epicenter coordinates and the desired radius of investigation, the computer printed out a list of all dams within this area in a matter of minutes. The list included the dam name and identification number, type of dam, longitude and latitude coordinates of each dam, the distance from the epicenter in miles, and the owner of each dam. For the Morgan Hill earthquake, a total of 85 dams were identified for investigation. To prioritize the investigation, the owners of all dams within a 20 mile radius of the epicenter were contacted by telephone (estimated peak bedrock acceleration 0.1g). The owners of these 31 dams, were requested to inspect their dams and report back to DSOD. Within a few hours nearly every owner had responded. Two major dams, Leroy Anderson and Coyote, had reports of visible damage, but there was no reported indication of potential loss of life or property. The following day the remainder of the owners of the 85 dams within the area of investigation were contacted by telephone for a report on the condition of each dam.

Assessment

On April 25, 1984, a DSOD team consisting of two engineers from the Design Engineering Branch, one engineer from the Field Engineering Branch, and an engineering geologist inspected Leroy Anderson and Coyote Dam. The team observed trenching in progress on the crest of Leroy Anderson dam. An assessment was made at that time that no emergency repairs would be required at either dam, and that any change in operation such as lowering the reservoir, would not be necessary Ultimately, every jurisdictional dam within a 20-mile radius of the epicenter was inspected by engineers from the DSOD Field Engineering Branch.

Table 1 presents a list of those dams. Included in the table is the approximate peak horizontal ground acceleration estimated at each dam based upon an interpolation of data from the California Division of Mines and Geology and the United States Geological Survey strong motion instruments. Three of the embankment dams listed were actually instrumented and the table notes the peak base horizontal acceleration recorded in those instances. As anticipated, the table shows that the effects of the earthquake are more prevalant in areas of high acceleration, but not necessarily coincident with epicentral distance.

Grant Company No II dam is less than 3 miles northwest of the epicenter. The reservoir is impounded by the earthfill main dam and 3 saddle dams. There was no damage to any of the embankments or to the appurtenant structures. Several fresh dessication cracks on the embankments appeared to have been initiated by the earthquake. While these features do not impact the safety of the structure or constitute damage, their appearance should be noted. Primarily, the cracks were seen to run adjacent and parallel to the edges of the crest with one occasionally oriented transverse to the dam axis. They appeared to be only a few inches deep, although no exploration was carried out. It is the writers opinion that the substantial ground shaking at the dam enhanced the surface cracking which naturally occurs due to the drying out of the brittle, clayey topsoil. This very minor effect may have been overlooked in the inspections of other dams of similar construction.

The only significant damage reported near the epicenter was at Kuhn Dam, 4 miles to the southwest. An external patch on the outlet pipe was displaced allowing an uncontrolled release of water estimated at 30-50 gallons per minute. The 6-inch outlet pipe had been repaired in the mid-1960's with this patch held in place by steel bands. The gravity outlet is located some 300 feet from the main embankment and has a downstream control valve. The "break" occurred about midway between a small saddle dam and the downstream valve - about 25 feet from each. The leakage did not appear on the surface for a day or two after the earthquake. The dam owner reported that his residence nearby had sustained quite a bit of damage.

At Almaden Dam, 14 miles southwest, cracking of the concrete slab on the upstream face of the embankment was observed. Santa Clara Valley Water District (SCVWD) personnel made this observation on a follow-up inspection two days after the earthquake. Inspection reports made by other SCVWD people on the day of the earthquake did not reveal this cracking, and DSOD inspections did not record this observation. In any event, the effect to the structure was minimal and does not impact its integrety.

Leroy Anderson Dam, 12 miles southeast of the epicenter, experienced 0.63g horizontal acceleration at the crest and 0.41g at the toe. These peaks occurred at AZ 250°, at right angles to both the alignment of the Calaveras fault and to the axis of the dam. This zoned earthfill dam was completed in 1950. Damage consisted of longitudinal cracks about 20 feet apart and about 10 feet in from the upstream and downstream edges of the crest. The upstream crack was essentially continuous and opened as much as 3/4 inch. Minor differential settlement had occurred only in one small area. The downstream crack was discontinuous and open 1/4 inch or less. These cracks coincide with the contact between the clay core and clayey gravel stability sections. A seismic stability analysis was completed in 1977 for the maximum credible earthquake event for this dam by W. A. Wahler and Associates and subsequently reviewed by DSOD. These evaluations

concluded that the embankment would remain stable in the MCE, but some settlement of the embankment might occur. Because the compacted clay core of the dam is much stiffer than the dumped rockfill shell zones, this predicted settlement would be different between those zones. Thus, the performance of the embankment during the Morgan Hill Earthquake was similar to that predicted for the MCE analysis.

Flows from the outlet pipe were cloudy after the quake. They cleared up within a few days, and it is thought that the cloudiness was caused by disturbance of the silt on the reservoir bottom, not as a result of damage to the outlet.

Coyote dam, a zoned earthfill structure, was completed in 1936. It is in the Calaveras fault zone, 16 miles southeast of the epicenter. A seismograph on the left abutment recorded a peak horizontal acceleration of 1.29g at AZ 285°, at a 45 degree angle to the trace of the Calaveras fault.

During the April 25 inspection minor cracking was observed near the seismograph on the left abutment, on a ridge parallel to the spillway, and in fresh gunite above the left spillway wall. Dumped roadway fill on the upstream embankment was badly cracked. Water flowing from the outlet was quite muddy.

A follow-up visit was made on May 1, 1984, by DSOD personnel after the reservoir had been lowered about 15 feet. Cracks were observed in the upstream embankment running parallel to the crest about 3 feet above reservoir water surface. These cracks were not continuous probably due to the nature of the riprap surface; however they appear to be consistant along a line at that elevation. The maximum crack opening was 3 inches, but average crack width was much less. No significant slumping or offset was observed.

Surveys by SCVWD indicated that the earthquake caused a maximum vertical settlement of a little more than 0.2 feet, or 0.4 percent of the embankment height.

Discussion

Acceleration records indicate that the effect of directivity of the earthquake was quite significant and this phenomena is reflected in the type and level of damage to dams in the area. The intensity of ground shaking in this event seemed to be centered about the trace of the Calaveras Fault and not merely the earthquake epicenter. Further work is required to determine if the character of this particular motion, especially in the near field, had any special effect on the level of observed damage.

Conclusions

Little or no damage was observed to dams in the epicentral area. Minor damage occurred where directivity focusing of energy produced unpredictably high accelerations. All dams performed as predicted or better considering the high recorded accelerations.

Acknowledgements

The writers wish to thank the Field Engineering Branch for furnishing copies of inspection reports. Review and constructive comments by DSOD engineers were appreciated.

Photographs were furnished by Kathlin Hajas, Design Engineer.

Leroy Anderson Dam-cracking on the crest road.

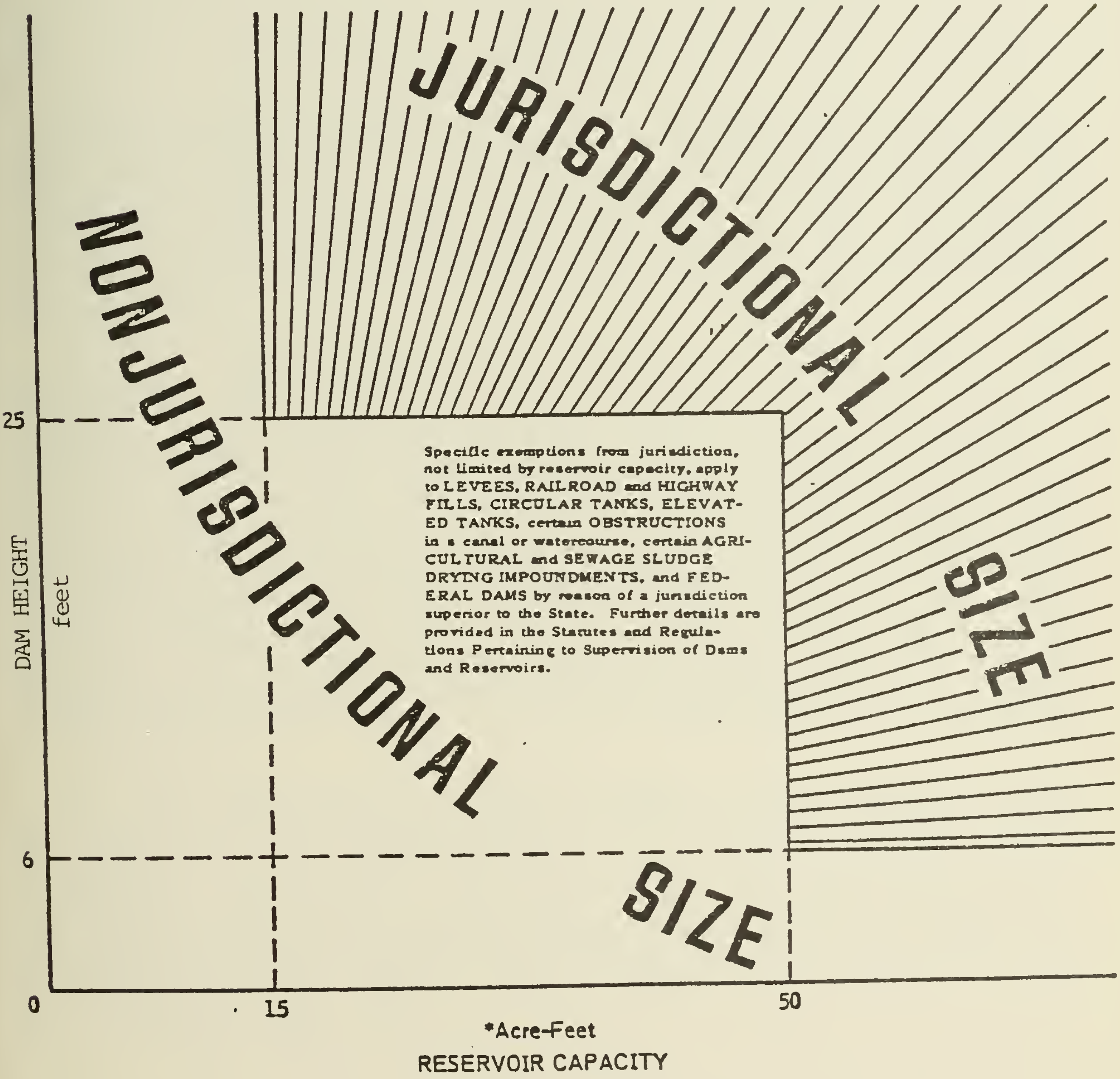
Coyote Dam-cracking on the upstream slope.

TABLE I
DAMS INSPECTED AFTER MORGAN HILL EARTHQUAKE , APRIL 24, 1984

NAME OF DAM	DAM NO.	STORAGE CAPACITY (AC-FT)	YEAR COMP	TYPE	HEIGHT (FEET)	EPICENTRAL DISTANCE (MILES)	DISTANCE TO FAULT (MILES)	MAX ACCEL (G)	REMARKS
JAMES H TURNER	10-21	50500	1964	ERTH	193	20.0	7.0	0.02	NO EFFECT
CALAVERAS	10	100000	1925	HYDF	210	14.3	0.1	0.05	NO EFFECT
SAN FELIPE RANCH	1621	64	1959	ERTH	49	2.0	0.7	0.4	NO EFFECT
GRANT COMPANY 2	1057-2	600	1927	ERTH	27	2.6	0.0	0.3	NO EFFECT
ED R LEVIN	1057	150	1968	ERTH	38	13.7	2.0	0.05	NO EFFECT
ISABEL LAKE NO 2	1625-2	95	1948	ERTH	18	8.3	8.0	0.1	NO EFFECT
ISABEL LAKE NO 1	1625	340	1948	ERTH	21	7.7	8.0	0.1	NO EFFECT
LAUREL SPR CLUB	1624	250	1968	ERTH	28	10.7	6.5	0.2	NO EFFECT
R SIMONI IRRIG	1622	152	1961	ERTH	44	16.0	8.5	0.15	NO EFFECT
UVAS	1006-2	10000	1957	ERRK	118	17.3	8.5	0.15	NO EFFECT
ELMER J CHESBRO	1006	8086	1955	ERRK	95	13.9	6.5	0.15	NO EFFECT
HIGUERA	629	65	1953	ERTH	44	15.2	3.5	0.05	NO EFFECT
SELVAGE NO 2	625	24	1948	ERTH	42	18.8	5.5	0.2	NO EFFECT
KUHN	624	85	1947	ERTH	67	3.6	2.3	0.25	OUTLET BK
COLUMBINE	622-15	60	1963	ERTH	24	6.6	2.5	0.2	NO EFFECT
ALMADEN VALLEY	622-14	27	1965	ERTH	38	12.0	10.0	0.05	NO EFFECT
AUSTRIAN	622-13	6200	1950	ERTH	185	12.0	17.0	0.05	NO EFFECT
WILLIAMS	622-4	160	1895	GRAV	69	18.4	16.0	0.05	NO EFFECT
RINCONADA RES	72-10	46	1969	ERTH	40	17.2	16.0	<0.05	NO EFFECT
LEROY ANDERSON	72-9	91300	1950	ERTH	235	10.8	1.2	"0.41"	CRACKING
LEXINGTON	72-8	21430	1953	ERTH	205	18.7	18.0	"0.02"	NO EFFECT
VASONA PERCOL	72-6	660	1935	ERTH	32	16.3	15.5	<0.05	NO EFFECT
GUADALUPE	72-5	3460	1935	ERTH	142	13.6	12.0	0.05	NO EFFECT
ALMADEN	72-4	2000	1936	ERTH	110	13.3	11.0	0.1	SLAB CRK
CALERO	72-3	9300	1935	ERTH	90	11.1	8.0	0.1	NO EFFECT
MURRY	1-79	715	1957	ERTH	54	16.6	9.0	0.1	NO EFFECT
KELLY CABIN CANYON	1-78	70	1955	ERTH	32	19.3	6.3	0.15	NO EFFECT
COIT	1-77	275	1956	ERTH	54	18.6	7.0	0.15	NO EFFECT
CHERRY FLAT	24	500	1936	ERTH	60	6.9	1.0	0.2	NO EFFECT
COYOTE	72-2	24500	1936	ERRK	140	15.5	0	"1.3"	CRACKING
COYOTE PERCOL	72	72	1934	FLBT	24	7.0	5.0	0.15	NO EFFECT

FIGURE 1

PROVISIONS OF DIVISION 3 OF THE CALIFORNIA WATER CODE
AFFECTING JURISDICTION OVER DAMS AND RESERVOIRS



*Metric units not specified in the Water Code are:

1.83 metres = 6 feet	18.50 cubic dekametres = 15 acre-feet
7.62 metres = 25 feet	61.68 cubic dekametres = 50 acre-feet

PERFORMANCE OF ANDERSON AND COYOTE DAMS DURING THE MORGAN HILL EARTHQUAKE OF 24 APRIL 1984

by

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Richard L. Volpe [2]
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ABSTRACT

Within a 20-mile (32-km) radius of the epicenter of the Morgan Hill earthquake there are 14 major dams and many more large enough to be under the jurisdiction of the State of California. Numerous small agricultural and private recreational dams also exist within the felt area. This report concentrates on the performance of two large earth and rockfill dams owned by the Santa Clara Valley Water District. Only at these two dams (Leroy Anderson and Coyote) and at one small privately-owned dam (Kuhn) did the earthquake cause "damage".

At Leroy Anderson Dam, 16 km from the epicenter, maximum crest accelerations were 0.63 g and 0.39 g horizontal and 0.20 g vertical. Earthquake effects at Anderson Dam were limited to minor seiching and to formation of shallow narrow cracks on the crest near the buried shoulders of the core. At Coyote Dam, 25 km from the epicenter, maximum accelerations at the left downstream edge of the crest were 1.29 g and 0.72 g horizontal and 0.40 g vertical. Earthquake effects at Coyote Dam were more widespread than at Anderson Dam. Longitudinal cracks were sparsely scattered in a zone near the waterline on the upstream face and additional minor cracking was found near each abutment and at other locations. A classic, though small, pattern of crest settlement was found at Coyote Dam: maximum settlement was 0.25-foot near the line of maximum section, tapering to minor settlement near the abutments. Pore pressure increases of 12 to 23 percent over pre-earthquake pressures were measured the day after the earthquake at the three piezometers at Coyote Dam.

The owner plans to repair the cracks at Anderson Dam by excavating shallow trenches along them and replacing the excavated material compacted to match the properties of the adjoining material. The cracks at Anderson Dam are functionally insignificant. The repair will reduce future road surface maintenance. The cracks at Coyote Dam are also functionally insignificant. The smaller crest cracks have essentially been obscured and partly sealed by dust and vehicle wheel loads and no benefit would be obtained by attempting to seal them or the other cracks. Hence, no "repair" of the "damage" at Coyote Dam is presently deemed necessary.

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INTRODUCTION

On April 24, 1984, 1:15 p.m. Pacific Standard Time, a widely felt tremor, subsequently named the Morgan Hill earthquake, jolted the San Francisco Bay Area and Central California. Following the Morgan Hill earthquake, field engineers from the Division of Safety of Dams (in the California Department of Water Resources) inspected 39 dams for earthquake damage. Emphasis was placed on the inspection of dams within a 20-mile radius of the epicenter (B. Shurtleff, personal communication). Damage was observed only at three dams: Leroy Anderson, Coyote, and Kuhn. The performance of Leroy Anderson and Coyote Dams will be discussed in detail in this paper. The damage at Kuhn Dam consisted only of the "popping off" of an old patch on the outlet pipe, located near the downstream valve, and resulted in "some water loss" (B. Shurtleff, personal communication), but neither the damage nor the loss of water appeared to be significant. No earthquake damage has been reported for small dams in Santa Clara County (J. Berkland, G. Orr, personal communications). In the remainder of this paper, Leroy Anderson Dam will be referred to as Anderson Dam. Where not otherwise referenced, basic data from the post-earthquake investigations of Anderson and Coyote Dams are from Tepel (1984a and 1984b, respectively) and R. L. Volpe & Associates (1984). This paper expands on an earlier informal work of the authors (Bureau and others, 1984). In this paper, all dates given only by month and day are in 1984.

Earthquake effects discussed in this paper include ground shaking, seiching, settlement, development of cracks, and pore pressure response. Although both dams were severely shaken, the other earthquake effects differed markedly at the two dams as discussed herein.

Figure 1 shows the location of the affected dams and other selected dams. Table 1 lists the maximum accelerations and epicentral distances for all strong motion accelerometers at dams which were triggered by the earthquake. (Table 1 and figures are at the end of the text, following the references). Instruments at Bethany, Contra Loma, and Del Valle Dams were not triggered (R. Maley and P. Morrison, personal communications). Instruments at San Luis, Lexington, and Briones Dams were triggered but recorded low peak accelerations of 0.06 g or less.

EMERGENCY RESPONSE

Immediately after the earthquake the Santa Clara Valley Water District post-earthquake dam inspection program was activated. This procedure calls for a group of District technicians to proceed automatically to pre-assigned dams and conduct inspections guided by forms tailored to each dam (the program is described by Tepel and others, 1984). Simultaneously, the District's Emergency Operations Center was activated. The first reports received by the District regarding Anderson and Coyote Dams were by radio from Santa Clara County Parks Department rangers working near the reservoirs. District technicians had reported back by radio on inspections of eight of the District's largest dams within one and one-half hours after the earthquake. By prearrangement, the District's contract flight service was about to independently dispatch a helicopter to District Headquarters when they received the District's confirming telephone call. The helicopter carried senior District personnel to both Anderson and Coyote Dams for on-site

inspections. These inspections, plus aerial reconnaissance of some other District dams, were completed within two and one-half hours after the earthquake.

Based on all the inspections, first priority for detailed examination was assigned to Anderson Dam where a backhoe was used on April 25 and 26 to explore the cracks in the crest. Detailed examination of Coyote Dam began on April 27; backhoe trenches and hand-dug test pits were dug there on May 3 and some crack mapping and monitoring of cracks continued into June.

SEISMIC AND GEOLOGIC SETTING

The reader is referred to other papers in this volume, to the compilation of Hoose (1984), and to Toppozada (1984) for basic descriptions of the Morgan Hill earthquake and the seismic history of the area. The Calaveras fault trends nearly parallel to the centerline of Anderson Reservoir at about a mile east of the dam. Coyote Reservoir is contained within the narrow rift valley formed by the fault zone. The main branch of the fault underlies the foundation of Coyote Dam. Both dams are located near the southern extremity of the April 24 rupture, where the strongest shaking was concentrated. Figure 1 shows the geographic relationship between the causative fault and the two dams.

The geology of Anderson Dam site has been described by Marliave (1949), summarized by W. A. Wahler & Associates (1977a) and mapped from an environmental geology standpoint by Wagner (1978). Anderson Dam is situated across Coyote Creek where it leaves the foothills of the Diablo Range and enters the Santa Clara Valley. The foundation of Anderson Dam consists of sandstone, shale, greenstone, and serpentine of the Franciscan assemblage. The Coyote Creek fault system crosses the foundation area of the dam. A well-developed branch of the Coyote Creek fault was recently exposed in the spillway approach channel (Wahler Associates, 1984); the age of most recent displacement at this location has been estimated on a reconnaissance basis as at least 100,000 years by Shlemon (1983).

The geology of the Coyote Dam site has been described by Tolman (1934) and summarized by W. A. Wahler & Associates (1977b). Regional geologic mapping of the dam and vicinity is found in Williams and others (1973). Coyote Dam is built across Coyote Creek about six miles upstream of Anderson Dam. The foundation of the dam is mostly faulted rocks of the Franciscan assemblage in the left abutment, channel section, and lower right abutment. The upper right abutment and spillway are founded in Berryessa formation (Cretaceous shale with basal conglomerate). The fact that the dam site spans the fault valley of the Calaveras fault was recognized during the design exploration. The dam was designed to withstand horizontal displacements of up to 15 feet and vertical displacements of up to five feet in the fault zone (Tibbetts, 1936). A recent seismic stability evaluation (W. A. Wahler & Associates, 1977b) concluded that the dam could safely withstand a magnitude 7.5 earthquake on the Calaveras fault (accompanied by supposed offsets derived from modern criteria: 10 to 16 feet of horizontal displacement and four feet of vertical displacement) without catastrophic release of water.

PERFORMANCE OF ANDERSON DAM

General Description of Anderson Dam

The 235-foot-high Anderson Dam, completed in 1950, has a crest length of 1,430 feet, a freeboard of 15 feet above spillway crest, a crest width of about 40 feet, and both faces slope at 2:1 (horizontal to vertical). The dam has upstream and downstream shells of dumped and sluiced rockfill and a compacted central core of well graded gravelly sandy clay. At the time of the earthquake the water level of the reservoir, which has a capacity of 91,300 acre-feet, was 26.4 feet below the spillway crest elevation of 625.0. Anderson Dam is 16 km from the epicenter of the Morgan Hill earthquake. An aerial view of the dam is shown in Figure 2.

Crest Cracks

Minor damage was caused to the dam by the earthquake in the form of two systems of longitudinal cracks on the crest road roughly 20 feet apart and centered over the buried shoulders of the core. To observe the pattern and extent of cracking with depth, seven backhoe trenches were excavated on the crest. Most trenches were excavated to a depth of about 5 feet, but one trench located near the maximum section was extended to a depth of 10 feet. Typically, the cracks were open about 3/4-inch at ground surface near the maximum section and faded to hairline cracks near the abutments. In scattered places, up to one inch of vertical offset could be seen at the surface, the side toward the near face of the dam being down. The downstream crack system extended over a length of about 920 feet and the upstream system about 1,100 feet. The upstream cracks were typically two to 3-1/4 feet in depth; the maximum depth was about 6-1/2 feet at a point near the maximum section. The downstream cracking was generally less severe than the upstream and averaged two to 2-1/2 feet in depth. Figures 3 and 4 show the cracks on the upstream side of the crest and a closeup of the surface crack openings.

We believe that the cracks developed over the buried shoulders of the core because (1) the core and shell reacted differently to the earthquake shaking, and (2) in places more earthquake-induced settlement occurred within the rockfill shells than in the core. Observation of the trench walls suggests that the cracks were generally confined to a cohesionless roadfill material placed on the crest at various times after construction. The seven trenches intersected nine cracks because two trenches were dug at sites of paired cracks such as shown in Figure 4. Of the nine cracks explored, only three actually penetrated the core below the roadfill. The depths of crack penetration into the core were approximately three and six inches at two sites where the cracks were fresh and apparently entirely earthquake-induced. At the third site (shown in Figure 3) the crack penetrated about four feet into the core; here the earthquake-induced crack apparently propagated along a zone of pre-existing subsurface shear distortion which faded into the core-shell contact.

Survey data indicate that settlement of the dam occurred for about 25 years after construction and that the ultimate settlement at the maximum section amounted to 3.5 feet (W. A. Wahler & Associates, 1977a). As the post-construction settlement occurred, more material was needed to restore the

roadway grade. The cracks within the cohesionless roadfill appeared to follow pre-existing zones of shear distortion which, most likely, were caused by minor long-term differential settlement between the core and shell materials (R. L. Volpe & Associates, 1984). Repairs to the crest area have been estimated to cost about $30,000. The repairs will consist of excavating trenches along each crack system and then recompacting in place the excavated material. The cracks are functionally insignificant with respect to overall dam safety. The principal benefits of the repair work are improved appearance of the crest and reduction of possible future roadway maintenance costs by preventing enlargement of the cracks due to traffic.

Survey Monuments

Survey records at Anderson Dam are based on a line of 15 monuments on 100-foot spacing near the center of the crest. Post-earthquake surveys were performed on April 26 and compared with the prior routine annual survey of July 5, 1983. Anderson Dam had a maximum settlement of 0.05 foot and a maximum lateral (transverse) movement of 0.03 foot as measured at the monuments. The maximum lateral movement was measured in the upstream direction at one monument and the downstream direction at another. With respect to lateral movement and disregarding direction of movement, each monument has experienced greater year-to-year movement at some time in the period 1978-83 than was reported for the post-earthquake survey. With respect to settlement, four of the fifteen monuments indicated less settlement for the period July 1983 to April 26, 1984 than the maximum year-to-year settlement they had experienced in the five years prior to July 1983. For the same time periods, the other 11 monuments had post-earthquake settlement that exceeded their earlier maximum settlement by not more than 0.03 foot. The earthquake-induced amounts of vertical and lateral movement are considered to be insignificant with respect to overall dam safety.

Piezometers

Two pneumatic piezometers were placed in a boring drilled in 1975 for the seismic stability analysis of Anderson Dam (W. A. Wahler & Associates, 1977a). The piezometers are normally read monthly at about mid-month. The last readings before the earthquake were taken on April 18, and were consistent with earlier readings. Post-earthquake readings were taken each day, April 25-30, inclusive, and also on May 3. The locations of the piezometers are shown in cross section in Figure 5. At Piezometer No. 1, readings on April 25-27 were unchanged from the April 18 reading. They decreased slightly on April 28 and 29, then returned to the April 18 level. At Piezometer No. 2, the April 25 reading was the same as on April 18. Readings then trended slightly downward to 0.2 psi below April 18 level on April 29 and then trended slightly upward. No significant earthquake-induced changes in pore water pressure were detected.

Seiching

Seiching potential at reservoirs in Santa Clara County was mentioned briefly by Rogers and Williams (1974), who believed that Coyote Reservoir was the most likely candidate for significant seiche activity.

Anderson Reservoir has a hydrogauge sensor which provides continuous reservoir storage information. The gauge automatically records changes in water level exceeding 0.03 feet. Readings can be taken as often as every 15 seconds. The data are telemetered (rounded to the nearest 0.10 foot) to Santa Clara Valley Water District headquarters and stored on magnetic discs. The hydrogauge is located on the upstream face of the dam. Because the dam is offset from the main body of the reservoir (see Figure 2) the hydrogauge location at Anderson Reservoir is not suited to detect the most likely orientation of seiche action or maximum seiching. Nevertheless, the recorded reservoir elevation data indicate that a disturbance with a peak-to-peak amplitude of 0.4 foot and period of about three minutes did occur. The reservoir level returned to normal within about 15 minutes after the earthquake. Figure 6, from Tepel (1984a), is a generalized plot of short-term changes in reservoir elevation as reported from the hydrogauge.

Strong Motion Records and Embankment Performance

The Morgan Hill earthquake triggered numerous strong motion accelerometers in an extensively instrumented area. The records obtained at Anderson and Coyote Dams are particularly significant.

Anderson Dam is instrumented near the downstream toe and on the crest by the U. S. Geological Survey (USGS) which operates two Kinemetrics SMA-1 three-component strong motion accelerometers. The crest instrument, mounted on the floor of a small concrete vault at the upstream edge of the crest near the maximum section, recorded motions with peak horizontal accelerations of 0.39 g and 0.63 g, in the directions parallel and perpendicular to the crest alignment, respectively. Peak vertical acceleration was 0.20 g. The crest records involved about 12 seconds of strong motion with a bracketed duration at 0.10 g of 8.7 seconds. The downstream instrument, located on an alluvial foundation, recorded peak horizontal ground accelerations of 0.41 g and 0.30 g, and a peak vertical acceleration of 0.20 g, for a bracketed duration of 5.2 seconds. (Data from sources referenced in Table 1.)

The Anderson Dam crest motions are the largest accelerations recorded to date in the United States on the crest of an embankment dam. Prior to this earthquake, the largest accelerations recorded on embankment dams were 0.20 g on Santa Felicia Dam during the 1971 San Fernando earthquake (M = 6.5) and 0.52 g on Long Valley Dam during the 1980 Mammoth earthquake (M = 6.3).

The authors considered performing a dynamic response analysis with the two acceleration records obtained at Anderson Dam. The lack of information regarding the foundation conditions at the downstream instrument precluded the use of the corresponding record. The authors are aware of the benefits of using such records to validate current simplified or detailed methods of earth dam dynamic analysis. Such studies could be completed if additional foundation information for the downstream instrument becomes available.

PERFORMANCE OF COYOTE DAM

General Description of Coyote Dam

Coyote Dam, which is one of a few dams in the United States knowingly built across an active fault, was completed in 1936. The dam is 140 feet high, has a crest length of 980 feet and a crest width of 100 feet. At the time of the earthquake, the water level of the 23,700-acre-foot reservoir was 5.4 feet below the spillway crest elevation of 777.2. The dam has a unique section conceived by the designer (Tibbetts, 1936) to protect the embankment against internal erosion in case of fault offset in the foundation. The principal embankment material consists of a homogeneous, well compacted, moderately plastic, sandy clay. This impervious zone has a top width of 40 feet and slopes upstream and downstream at 2:1 (horizontal to vertical). Coarse gravel was placed on the upstream and downstream sides of the impervious section with the expressed intent to plug any transverse cracks that might occur during earthquake shaking. A coarse boulder zone (riprap) was placed over the gravel section to provide an adequate driving force for this crack filling action. The exterior slopes of the dam are approximately 3:1. Coyote Dam is 25 km from the epicenter. Figure 7 is an aerial view of the dam. Earthquake effects at Coyote Dam were widespread but minor in nature. Cracks were found in three areas: the upstream face, the crest, and the spillway and vicinity.

Earthquake-Induced Cracking

Upstream Face Cracks

Earthquake effects on the upstream face consisted of a discontinuous series of small cracks in reservoir sediment and slope wash deposits that had accumulated between the large boulders, and associated larger cracks which indicate possible dislocation of small groups of these boulders. The cracks were generally close to the maximum section of the dam and were seen from slightly below the water line to about El. 778. The cracks in the infilling sediment were generally open up to one to two inches and were a few feet long. The cracks affecting groups of boulders were open from several inches to about one foot wide, and were up to about 10 feet long. Maximum crack depth (determined by probing) was on the order of five to seven feet. At a few of the larger cracks, the downslope side had dropped as much as four to six inches. All of these cracks seem to be the result of rearrangement of the surficial boulders due to the earthquake. Figure 8 shows one of the typical cracks in the infilling sediment between boulders.

Cracks In and Near Crest and Spillway

A system of cracks, including two clearly traceable cracks, was found about 30 feet south of the California Division of Mines and Geology (CDMG) accelerometer location (see Figure 7). When observed shortly after the earthquake, one crack was about 35 feet long, 3/4-inch wide at most, and trended about N80^{o}E. A second, smaller, crack was discontinuous, about 20 feet long, and gently curved in plan. The cracks appear to be tension cracks formed in the embankment near a steep buried ridge. Further discussion of these cracks is in Shakal and others (this volume).

Two cracks appeared in an access ramp fill to the left of the spillway approach channel. One crack was essentially continuous and extended a little over 90 feet from the left log boom anchor southeasterly to the waterline. The other crack was discontinuous, locally present as an overlapping pair, and extended over a distance of 70 feet in a rough arcurate pattern from near the southeast end of the first crack to the west. None of the cracks in this area were open more than 1/2 inch at the surface. The cracks could not be traced below about 30 inches depth in two backhoe trenches. As the reservoir was drawn down in the following weeks, it became clear that the southeast end of the continuous crack was within a few feet laterally and perhaps two feet vertically of a bedrock surface exposed by the drawdown. No offset or cracking was observed in the bedrock along the trend of the crack. Minor tension cracks were also found in a soil-covered bedrock ridge between the spillway and the dam. These cracks represent the tops of incipient very thin slope failures which are of no operational consequence.

A few very minor cracks and spalls were noted in the concrete lining of the spillway. The cracks are thought to result from response of the lining to the earthquake shaking, rather than to landsliding of the steep spillway cut slopes. The spillway is crossed by a minor branch of the Calaveras fault. Long-term distortion of the spillway floor and walls in the fault area has led to the suggestion (Radbruch-Hall, 1974) that fault creep may have damaged the spillway. A later investigation (Earth Sciences Associates, 1977) concluded that most of the spillway floor heave was caused by rebound. Post-earthquake surveys of a monument line down the spillway did not indicate that significant horizontal or vertical movements had taken place.

None of the cracks noted at Coyote Dam was located or oriented to suggest that fault rupture occurred in the dam or spillway. No surface fault rupture has been noted at or in the immediate vicinity of Coyote Dam by the authors or by other investigators (e.g. Mathieson, 1984; Hart, 1984; and Harms and others, 1984) who examined much of the Calaveras fault after the earthquake. A seismic reevaluation of Coyote Dam completed in 1975 (W. A. Wahler & Associates, 1977b) concluded that fault offsets of as much as 16 feet horizontal and 4 feet vertical would not cause uncontrolled failure of the dam. No crack repair work is considered necessary at Coyote Dam. The outlet works operated normally after the earthquake.

Survey Monuments

Survey records for Coyote Dam are based on a line of monuments on 100-foot centers on the dam centerline. Vertical and horizontal surveys were taken on April 25 and June 7 and compared with the survey data of January 24, 1984. The results of the survey data are discussed below. Although the movements are significant to a discussion of earthquake effects, they are considered to be inconsequential with regard to overall dam safety.

Crest monuments 3 through 11 settled between January 24 and April 25, 1984 (Figure 9). Maximum settlement was 0.22 foot at monument no. 7. Between April 25 and June 7, minor additional settlement occurred at the same monuments; the maximum increment was 0.04 foot at monument no. 8. At monuments 3 through 11, the January 24-April 25 settlement exceeded the previously measured amounts by factors of 1.4 to 6.7, when compared to the

maximum survey-to-survey settlement measured semiannually since 1977. The January 24-April 25 settlement at monuments 3 through 11 varied from 0.14% to 0.38% of the embankment thickness at each monument.

At monuments 2 through 11, the maximum indicated horizontal (transverse) movements were 0.12 foot downstream at monument no. 8 and 0.03 foot upstream at monument no. 4, for the period January 24-April 25. Disregarding direction of movement, the amount of indicated movement at monuments 2 through 11 for the period January 24-April 25 varied from equalling to exceeding by a factor of 2.5 the maximum survey-to-survey transverse movements measured semiannually since 1977. The transverse movements are referred to here as "indicated" amounts because the line of sight to which they are referenced crosses the Calaveras fault zone and is therefore subject to change from tectonic sources.

Piezometers

Three pneumatic piezometers were installed at Coyote Dam in 1975 and 1976 in two borings drilled for the seismic stability analysis of Coyote Dam (W. A. Wahler & Associates, 1977b). The piezometers are shown in section view in Figure 10. The last readings before the earthquake were taken on April 18 and were consistent with earlier monthly readings.

At Coyote Dam a sharp pore pressure increase, measuring between 12 and 23 percent of the pre-earthquake pressure, was observed at the three piezometers. The first piezometer reading was not taken until about 24 hours after the earthquake; therefore, the maximum pore pressure increase was probably higher than measured at that time. At two of the piezometers, readings returned to pre-earthquake levels within 10 days. At the deepest piezometer, which is located just above the foundation contact but has its sensing zone slightly into the foundation, pore pressures remained above pre-earthquake levels until mid-June. Figure 11 shows the relative changes in pore water pressure as measured at the piezometers for the period April 18-June 14, 1984.

Seiching

Coyote Reservoir is equipped with a hydrogauge sensor essentially identical to the one described for Anderson Reservoir. The sensor is located about 1000 feet upstream of the dam on the left side of the 4.8 mile long reservoir. The hydrogauge data from Coyote Reservoir have a calibration jump of 0.5 foot that occurred sometime during the earthquake. A review of the data indicates that the instrument did not detect any seiching action in the reservoir.

Strong Motion Records and Embankment Performance

The Coyote Dam strong motion station, operated by CDMG, is located near the left abutment of the dam and close to the southern end of the presumed subsurface fault rupture. This station, underlain by a few feet of embankment, measured the largest horizontal acceleration ever recorded at ground level, 1.29 g (Shakal and others, 1984). The second horizontal component peaked at 0.72 g and the vertical component at 0.40 g. The records are reproduced elsewhere in this volume.

The two horizontal components of this record display several large amplitude excursions at intermediate frequencies (around 1 Hz) of interest to the designers of structures such as dams. Similar large, sustained acceleration pulses have sometimes been observed in near-field records. Such pulses, which affect ground motion records obtained at short distances from faults, may correspond to the effects of elastic rebound as the rupture propagates along the fault. The unusual shape of the Coyote Dam records may also reflect local geologic or topographic conditions, or the possible "stopping effect" (see, for example, Bakun and others, 1984) that might occur when a propagating rupture reaches an offset in a fault zone. CDMG has tested the performance of the Coyote Dam instrument, which indicated no improper operating characteristics. A record obtained in 1979 at the same station was considered normal. A second instrument was installed nearby by CDMG after the April 24 earthquake to provide comparison records (Shakal and others, 1984).

Lastly, it appears that both the Anderson and Coyote records may have been strongly influenced by "directivity" or "focusing" effects (Bakun and others, 1984), which can be simplistically compared to the Doppler effect in acoustics. In the case of an earthquake, "directivity" effects (Bolt, 1981) may result in increasingly larger amplitudes and modifications of the frequency content as the motion propagates along the fault in the direction of the rupture.

CONCLUSIONS

The Morgan Hill earthquake generated substantial shaking at both Anderson and Coyote Dams but little damage occurred. Both dams performed satisfactorily with fairly high reservoirs. Indeed, in the authors' opinion, the earthquake effects at the dams were less severe than might have been expected from the seismological data. The range and severity of earthquake effects (i. e., the nature and extent of cracking, recorded accelerations, vertical and horizontal movement, seiching, and earthquake-induced pore pressures) varied substantially at the two dams. The recorded ground surface accelerations at both dams confirm that well-compacted earth-rockfill dams on a firm foundation will perform satisfactorily during strong earthquake shaking of moderate duration.

ACKNOWLEDGEMENTS

We would like to thank the following people for their help in furnishing information for this paper: Leroy Fail, Joe Fedock, Dick Maley, Paul Morrison, Roger Sherburne, Burt Shurtleff, and Dave Sparks. Dames and Moore contributed drafting services. The Santa Clara Valley Water District provided word processing services.

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TABLE 1

PRELIMINARY MAXIMUM ACCELERATION DATA FROM TRIGGERED INSTRUMENTS AT EMBANKMENT DAMS, MORGAN HILL EARTHQUAKE

Dam	Epicentral Distance (km)	Component Direction (deg)	Maximum Acceleration (g)
Anderson		340	0.30
Downstream	16	up	0.20
		250	0.41
Anderson		340	0.39
Crest	16	up	0.20
		250	0.63
Briones	84	142	0.02
Left		up	0.01
Abutment		52	0.02
Left Crest		140	0.02
		up	0.01
		50	0.02
Center Crest		133	0.02
		up	0.01
		43	0.02
Coyote	25	285	1.29
		up	0.40
		195	0.72
Lexington	27	90	0.02
Left		up	0.01
Abutment		360	0.02
Left Crest		90	0.02
		up	0.02
		360	0.03
Right Crest		90	0.03
		up	0.03
		360	0.04
San Luis	60	240	0.06
Left Crest	(approx.)	down	-
		150	0.06

Data Sources: CSMIP and SMIRS data banks, Shakal and others (1984), Brady and others (1984), and Paul Morrison (written communication)

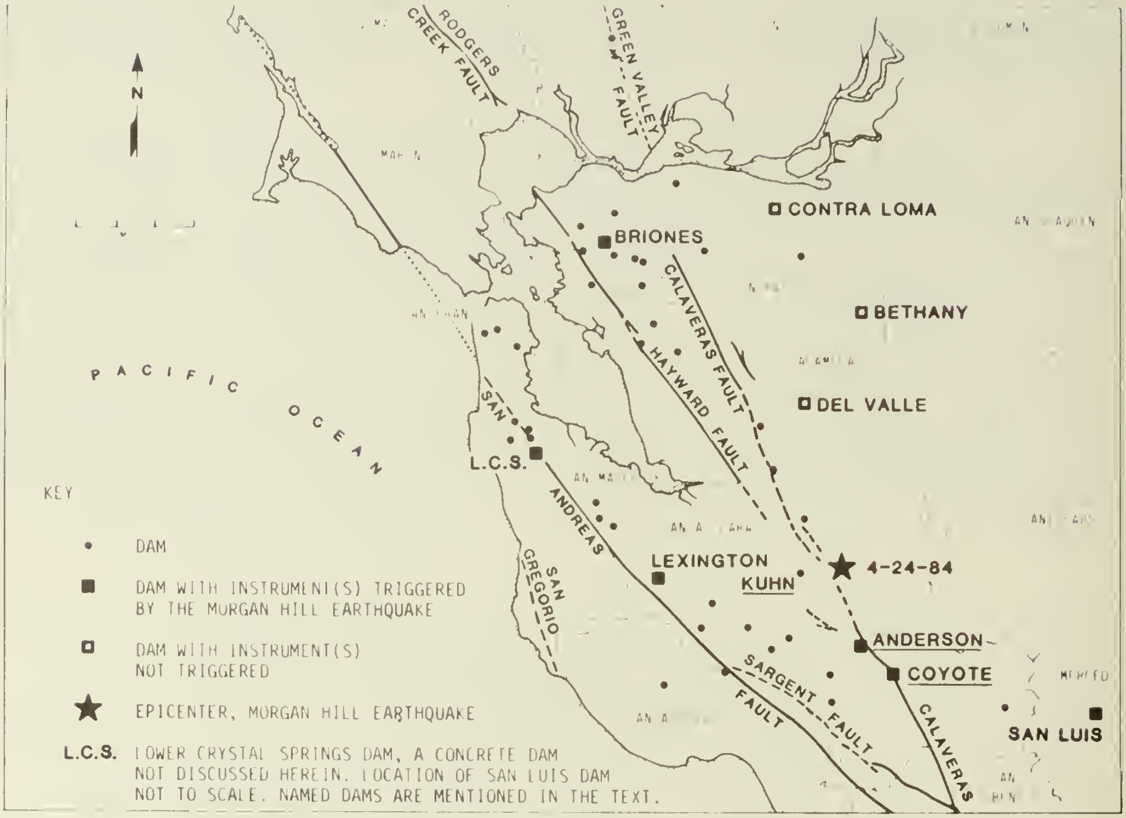

Figure 1. DAM AND FAULT LOCATIONS (After Buangan and Wahler, 1980).

Figure 2. AERIAL VIEW OF ANDERSON DAM, TAKEN AUGUST 8, 1984. CREST ACCELEROMETER IS IN CONCRETE VAULT JUST BEYOND ANGLE POINT. DOWNSTREAM ACCELEROMETER IS JUST OUTSIDE THE FIELD OF VIEW, TO THE LEFT OF THE TWO WHITE-ROOFED BUILDINGS.

Figure 3. EXPLORATION TRENCH AND CREST PAVEMENT CRACK NEAR UPSTREAM EDGE OF ANDERSON DAM

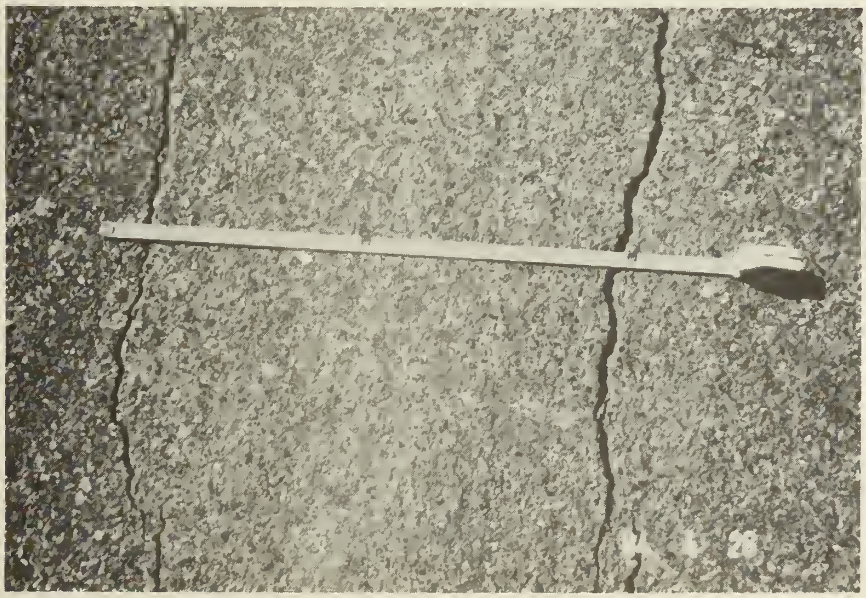

Figure 4. DETAIL OF PAIRED CRACK SYSTEM IN CREST PAVEMENT, ANDERSON DAM. CRACKS ARE ABOUT 21 INCHES APART AT MEASURING TAPE.

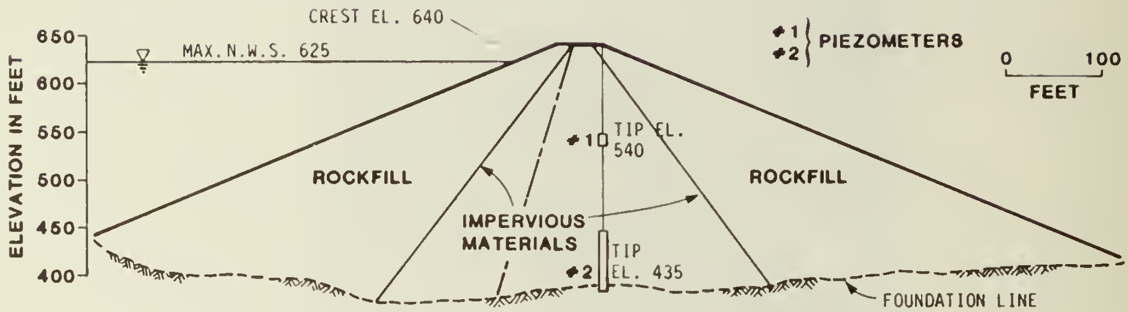

Figure 5. CROSS-SECTION OF ANDERSON DAM, SHOWING PIEZOMETER LOCATIONS.

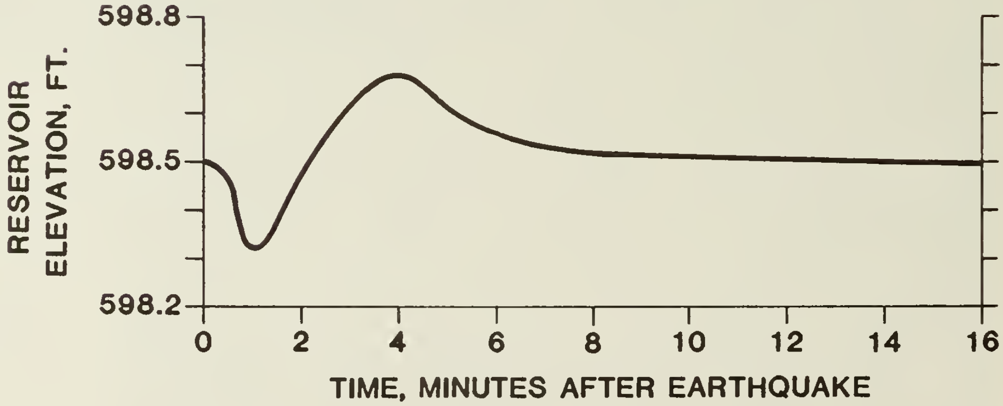

Figure 6. CHANGE IN WATER LEVEL AT ANDERSON RESERVOIR AFTER THE MORGAN HILL EARTHQUAKE. TIME OF BEGINNING OF SEICHE ACTION IS KNOWN ONLY WITHIN ABOUT ONE MINUTE.

Figure 7. AERIAL VIEW OF COYOTE DAM, TAKEN AUGUST 8, 1984. SPILLWAY LINING REPLACEMENT WAS IN PROGRESS. CDMG ACCELEROMETER IS AT DOWNSTREAM EDGE OF CREST AT LEFT ABUTMENT, NEAR PROMINENT OUTCROP.

Figure 8. DETAIL OF CRACK IN INFILLING SEDIMENT BETWEEN SHELL BOULDERS, UPSTREAM FACE OF COYOTE DAM.

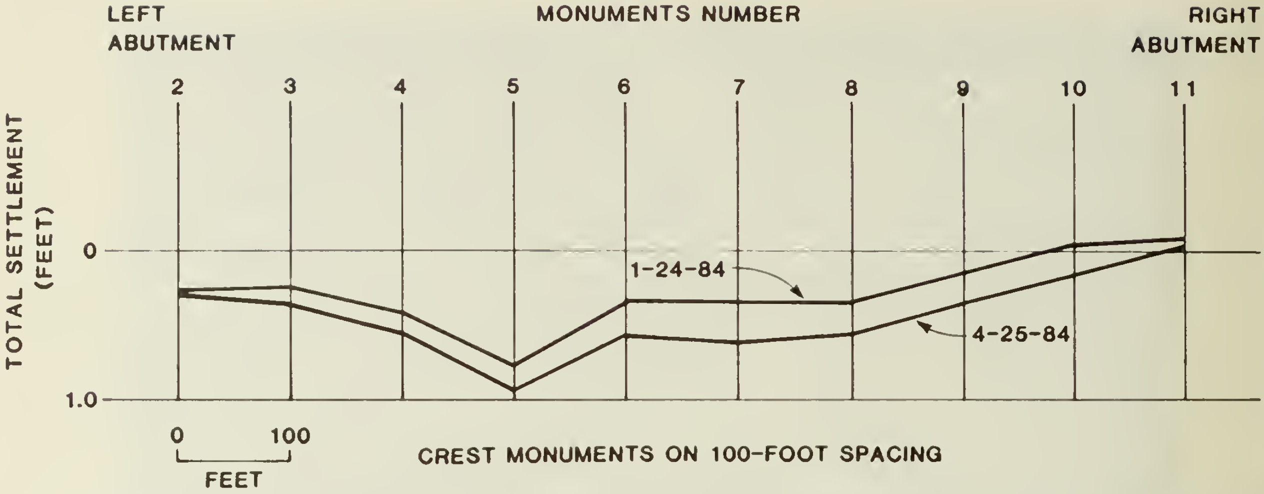

Figure 9. EARTHQUAKE-INDUCED SETTLEMENTS AT COYOTE DAM CREST MONUMENTS

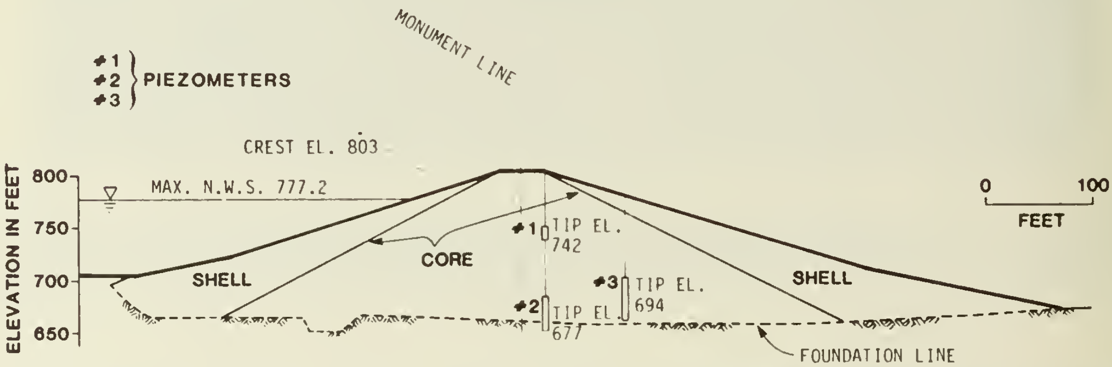

Figure 10. CROSS-SECTION OF COYOTE DAM, SHOWING PIEZOMETER LOCATIONS.

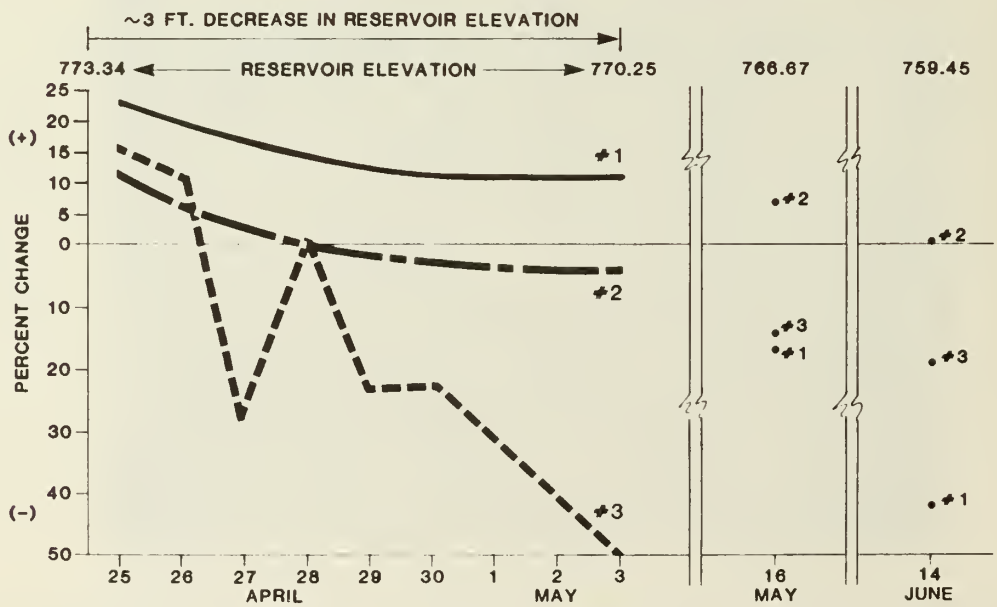

Figure 11. PERCENT CHANGES IN PORE WATER PRESSURES (Relative to April 18, 1984 Readings). NOTE ERRATIC RESPONSE OF PIEZOMETER #3.

THE 1984 MORGAN HILL EARTHQUAKE
EFFECTS NEAR COYOTE DAM

by

H. John Hovland, James C. Gamble, Bing J. Mah[1]

and

Julio E. Valera[2]

ABSTRACT

The April 24, magnitude 6.2, Morgan Hill Earthquake produced a horizontal peak ground acceleration of 1.29g at Coyote Dam. The strong motion instrument location and the nearby area were inspected for earthquake effects. This paper presents the observations made. While an unusually high acceleration value was recorded by the instrument, nearby structures suffered little or no damage. This observation will undoubtedly have implications on the selection of instrument locations, and the concept of free-field motion, as commonly used in earthquake engineering.

INTRODUCTION

On April 24, 1984, the Calaveras Fault, between Hall's Valley and Coyote Lake, slipped, producing an earthquake of magnitude 6.2. Felt throughout Central California, this earthquake caused tall buildings in San Francisco to sway for several seconds and triggered several strong motion instruments. The California Division of Mines and Geology (CDMG) Station 57217, located near the left abutment of Coyote Dam recorded peak ground accelerations of 1.29g with an azimuth of 285, 0.90g with an azimuth of 195, and 0.40g in the vertical direction. Because of the unprecedented 1.29g peak horizontal acceleration, and because of the potential implications for earthquake-resistant design of dams, the authors made a reconnaissance of Coyote Dam noting especially the instrument location and structures in the vicinity on May 7, 1984.

Various aspects of the Morgan Hill Earthquake have already been reported. Shakal, Sherburne, and Park (6) present strong motion records from the earthquake. Bureau, Tepel, and Volpe (2) describe the performance of Anderson and Coyote Dams during this earthquake. Graduate Students of Class CE 282D of Stanford University (3) present a damage report for the earthquake. Shakal,

1 Pacific Gas and Electric Company
2 Earth Sciences Associates

Gay, and Sherburne (5), and Bakun, et al (1) describe effects of the earthquake and seismological implications. Hart(4) reports on surface faulting associated with the earthquake.

This paper presents observations of surface and subsurface conditions at the strong motion instrument location and earthquake effects on nearby structures, which are not specifically considered in the above-referenced papers.

OBSERVATIONS AND COMMENTS

The Strong Motion Instrument Location and Vicinity:

Coyote Lake and the locations described in this paper are shown in Figure 1. The strong motion instrument is located near the left abutment on the south side of a large rock or outcrop of rock, as shown in Photo 1 and also in Figures 2 and 3. There was no evidence of relative movement between the concrete pad of the instrument housing and the ground.

The subsurface conditions at the instrument location were investigated by reviewing some of the construction drawings of the dam. Figure 3 shows plan and section views of Coyote Dam near the instrument. The instrument is located at approximately Station 6+50. Figure 3 reveals a very interesting preconstruction appearance of the rock outcrop. The rock appears as a truncated spur, with the Calaveras Fault located just east of the rock. The southern relief of the rock was more pronounced than at the present time, as shown on the sections. A significant amount of ground was cut away during construction, and the instrument is shown to be on about 20 feet of fill, the upper portion of which probably consists of gravel. Also, exploratory tunnels were driven into the rock, as shown, which were subsequently filled with grout.

There were a few en echelon ground cracks up to one-half inches wide about 15 feet southwest of the instrument, as shown in Photo 2 and in Figure 2. Toward their eastern end the cracks become subparallel to the dam, and their western end point approximately west. Their right-stepping en echelon pattern implies a tendency of the large rock or rock outcrop to move in a northerly or northwesterly direction during the earthquake.

A southwest view of the large rock is shown in Photo 3. The earthquake apparently produced a rock fall from the steep eastern face of this rock, as shown in Photo 3 and in the close-up Photo 4. Fresh, open cracks were present on top of the knob of rock, and the cracks extended all the way to the west side as shown in Photo 5. Note also the relative movement between the rock and the ground shown in Photo 5. The shaking may have caused the ground to slump relative to the rock, or the earthquake may have pushed up the rock relative to the ground. These features are also illustrated in Figure 2.

There were some fresh cracks in the ground on the upslope side of the road going to the downstream side of the dam, as illustrated in Figure 2. These cracks had an irregular, square mesh appearance with approximately a spacing of 8 to 10 inches. They were not typical of shrinkage cracks, since the ground

appeared moist and the crack edges appeared disturbed rather than smooth. These cracks may have been produced by lurching of the ground during the earthquake.

On the west side of the outlet control bridge at the downstream toe of the dam, there were some loose boulders on the shoulder of the road that appeared to have recently tumbled from the slope above the road, as shown in Photo 6.

Structures in the Area:

The outlet control structure is located below the dam less than one-fourth of a mile from the instrument. This structure (Photo 7) consists of a steel access bridge about 2.5 feet wide supported by 12-inch diameter concrete piers, ranging from an estimated 5 to 15 feet high. No apparent cracking or damage to the piers was observed.

A small control building is located approximately one-fourth of a mile south of the instrument; see Photo 8. The roof is a concrete slab about 5 inches thick. This makes the building rather top-heavy and vulnerable to damage from earthquake shaking. Judging from the concrete roof, it is possible that the walls of this building are reinforced. There were some fine, hairline cracks, mainly near the top of the walls. It could not be determined whether these cracks were old or new. The building did not appear to be damaged.

There is a rest area and boat launching ramp about 2.1 miles from the dam on the west side of the lake; see Figure 1 and Photo 9. We examined a restroom area which was constructed of concrete block with a wood roof. No cracks were found. There was also a 4-foot high, essentially free-standing wall at the end of the restroom area. The wall, which is about 8 feet long, showed no cracks. There was no evidence of damage or movements at the set of four tanks just west of the rest area. The tanks are mounted on concrete pedestals about 1 to 2.5 feet high. The pedestals are about 8 inches thick, and the tanks are about 4 feet in diameter.

A set of two brick (large brick or stone) outbuildings are located about 2.5 miles south of the dam. Some cracks in the area of the lintels above the windows, and a few diagonal cracks did not appear to be new. Otherwise, the buildings showed no cracking or damage.

Another camping area with two restroom facilities is located about 2.8 miles south of the dam. One showed no cracks at all; the other showed some fine hairline cracks which appeared to be old.

A bait shop with a bar is located about 3.6 miles southeast of the dam near the end of the lake, as shown in Figure 1. The owner reported that on the day of the quake many cans and other small objects were thrown from the shelves and some of the cans burst, but the wooden building had suffered no damage.

CONCLUSIONS

Our observations indicate an anomalous situation with very high peak ground accelerations recorded by the strong motion instrument at the left abutment of Coyote Dam, but very little or no damage to structures located in the vicinity along the Calaveras Fault. As described by Bureau, Tepel, and Volpe (2), Coyote Dam performed satisfactorily and suffered very little damage. As described above, structures in the vicinity, some of which are only 1/4 mile from the instrument location, suffered little or no damage. Indications of possibly significant shaking are found just on the west side of the Calaveras Fault, consisting of boulders dislodged from a road cut, and the rock fall and fractured rock knob or rock outcrop just north of the instrument, as described in this paper. We infer from this behavior that either:

1. The high peak ground accelerations recorded by this instrument reflect a very localized behavior or response, or that

2. Rather ordinary structures and earth dams can survive ground motions involving peak ground accelerations well over 1.0g with little or no damage.

This earthquake, and its effects, will undoubtedly be studied in great detail. The siting of the strong motion instrument may not be that unusual, however, and the possibility of highly localized effects, or other seismological or geological factors need to be considered in trying to interpret a strong motion record for engineering purposes.

ACKNOWLEDGMENTS

We appreciate the efforts by CDMG to solicit observations of the effects of this earthquake. We wish to express our appreciation to R. V. Bettinger, F. W. Brady, D. H. Hamilton, and G. C. Lenfestey who reviewed the manuscript and offered many valuable comments.

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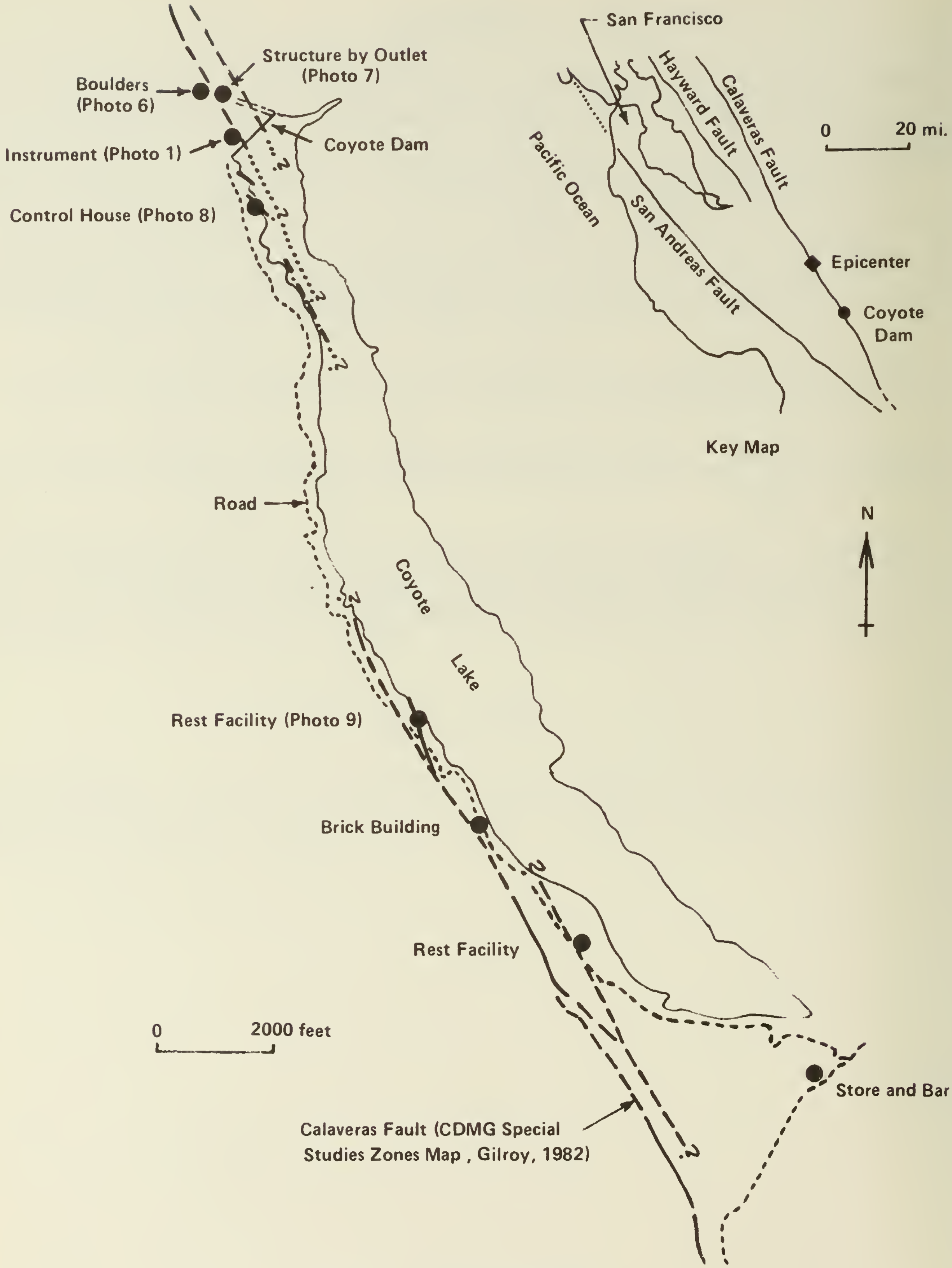


Figure 1 — Coyote Dam and Locations Described in this Paper

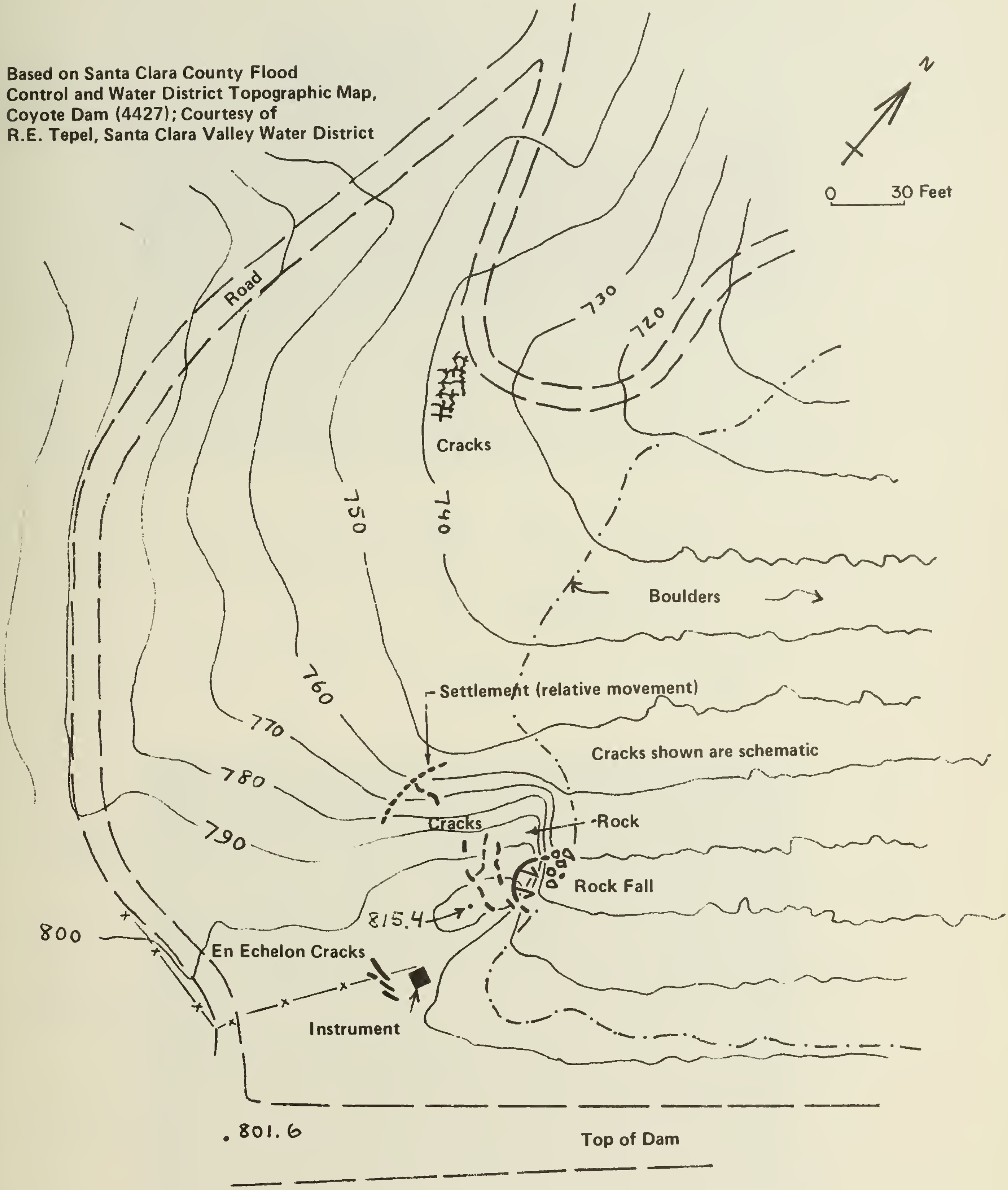


Figure 2 — Observations Near the Instrument

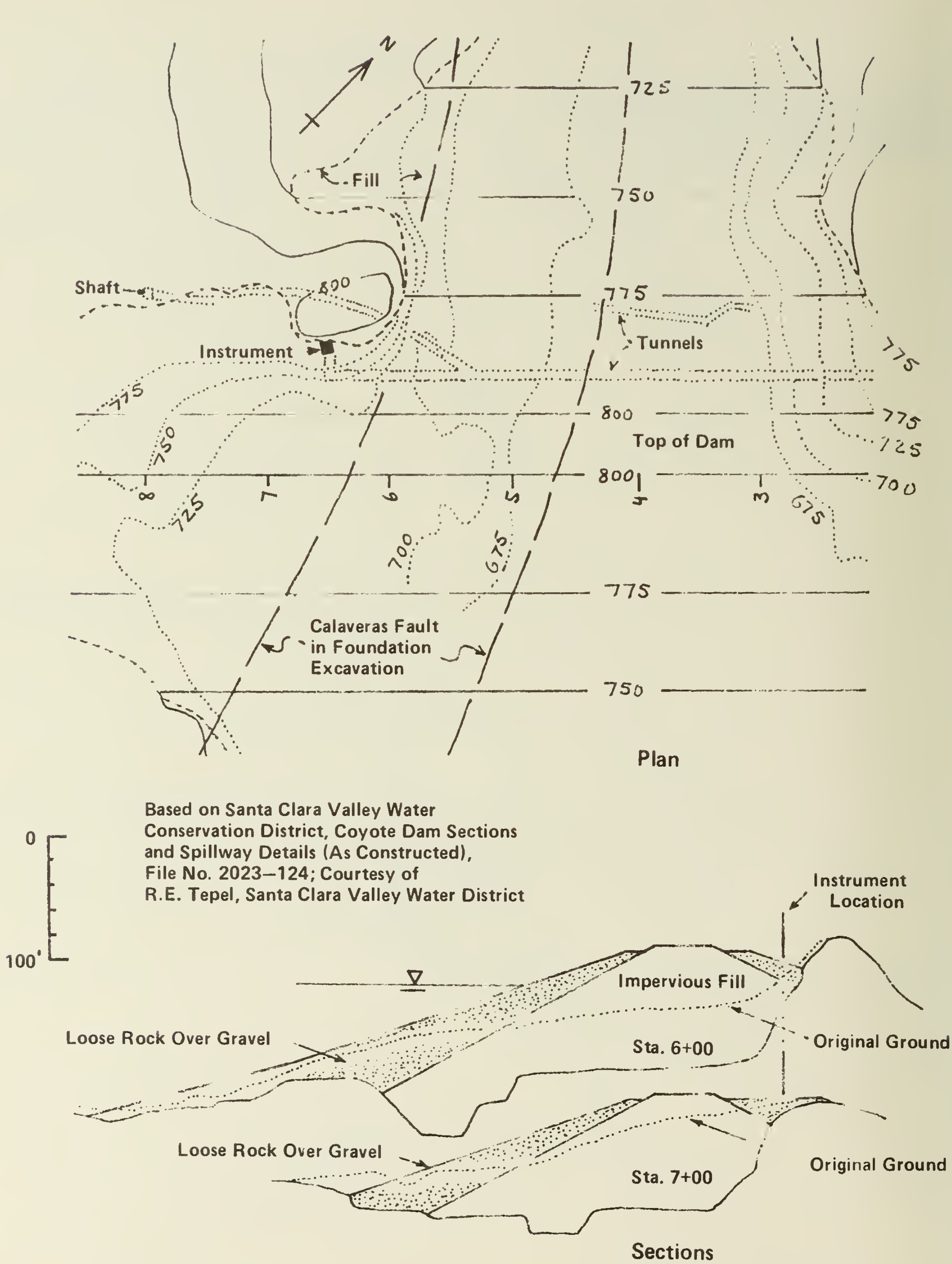


Figure 3 — Plan and Sections of Coyote Dam
Near the Strong Motion Instrument

Photo 1 - Northwest View of Instrument Housing

Photo 2 - En Echelon Cracks in the Ground about 15 Feet Southwest of the Instrument

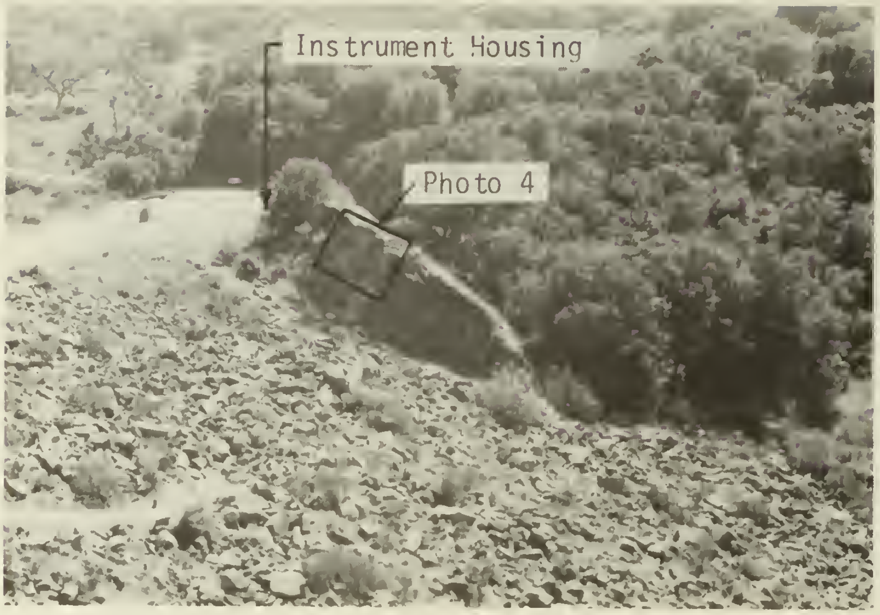


Photo 3 - Southwest View of Rock, Location of Rock Fall, and Instrument Location

Photo 4 - Close-Up View West of Rock Fall Location and the Fractured Rock

Photo 5 - Close-Up View East of the West Side of the Rock Showing a Fresh Crack and Relative Movement Between the Ground and the Rock

Photo 6 - Northwest View of a Location Northwest of the Dam Where Boulders Rolled from the Slope to the Shoulder of the Road

Photo 7 - Pier-Supported Structure and Walkway Around Pond by Outlet Structure -- No Damage

Photo 8 - Control Building Approximately 1/4 Miles South of Instrument -- No Damage

Photo 9 - Concrete Block Rest Facility Approximately
2.1 Miles South of Instrument -- No Damage

SUMMARY OF HIGHWAY BRIDGE DAMAGE
MORGAN HILL EARTHQUAKE, April 24, 1984

by

Richard Land and James Munro[1]

ABSTRACT

Only one bridge of 39 investigated was observed to sustain major structural damage. The county bridge carrying East Dunne Avenue over Anderson Reservoir, Br. No. 37C-166, was closed to traffic by a rock slide and suffered major damage.

BRIDGE DAMAGE SURVEY

The Caltrans Office of Structures Design Post Earthquake Investigation Team (PEQIT) investigated 39 bridge locations in the Morgan Hill area (Figure 1).

Time of Investigation: Between 1200 April 25, 1984 and
1400 April 26, 1984.

Team Members: Richard Land and James Munro

Bridge Locations:
Route 101 in Santa Clara County from post mile 4.94 to 35.76 (total 34 bridges).
Route 130 in Santa Clara County from post mile 2.0 to 15.8 (including 1 county bridge and 1 state bridge).
Route 17 in Santa Clara County at post mile 19.27 (1 bridge).
Route 680 in Alameda County at post mile 19.3 (1 bridge).
Santa Clara County bridge over Anderson Reservoir with a state designation of Br. No. 37C-166.

BRIDGE DAMAGE

Major Bridge Damage

A county bridge carrying East Dunne Avenue over Anderson Reservoir, Br. No. 37C-166, (about 4.5 miles east of Morgan Hill) was closed to

1 Associate Bridge Engineers, California Department of Transportation

traffic by a rock slide and suffered major structural damage (Photos 1 and 2). The structure has 6 spans of riveted plate girders on concrete columns with a timber deck and AC overlay with at least one concrete slab approach span.

Evidence indicates that this structure, which may cross the Calaveras fault, has been damaged previously. No attempt was made to differentiate recent damage from that done previously. Cable restrainers have been installed on this structure (Photos 3 and 4). The cables are attached to the bottom flanges of the girders and the pier caps primarily to provide transverse restraint. The restrainers accomplished this job very well. Most of the damage was caused by longitudinal movement with the greatest movement being near abutment 1 at the Morgan Hill end of the bridge. Longitudinal girder movements of almost 1 foot sheared off anchor bolts at the support adjacent to the end slab span at abutment 1 (Photo 5). This same movement transmitted forces through the restrainer cables to pier 2 knocking that pier out of plumb by almost 1 foot (Photo 6). The timber deck did not move as much as the girders because the deck rammed into the relatively stable end slab span (Photo 7). This difference in movement caused the transverse steel floorbeams (on top of the main longitudinal girders and under the longitudinal timber stringers and deck) to be pushed out of plumb by about 3 inches (Photo 8).

MINOR BRIDGE DAMAGE

Minor bridge damage was observed at one other structure, Coyote Cr. Br. No. 37-349 R/L, 04-SC1-101-19.2 (not open to traffic). The south abutment keys were slightly spalled because less than adequate provision was made for movement (Photos 9 and 10).

SUMMARY

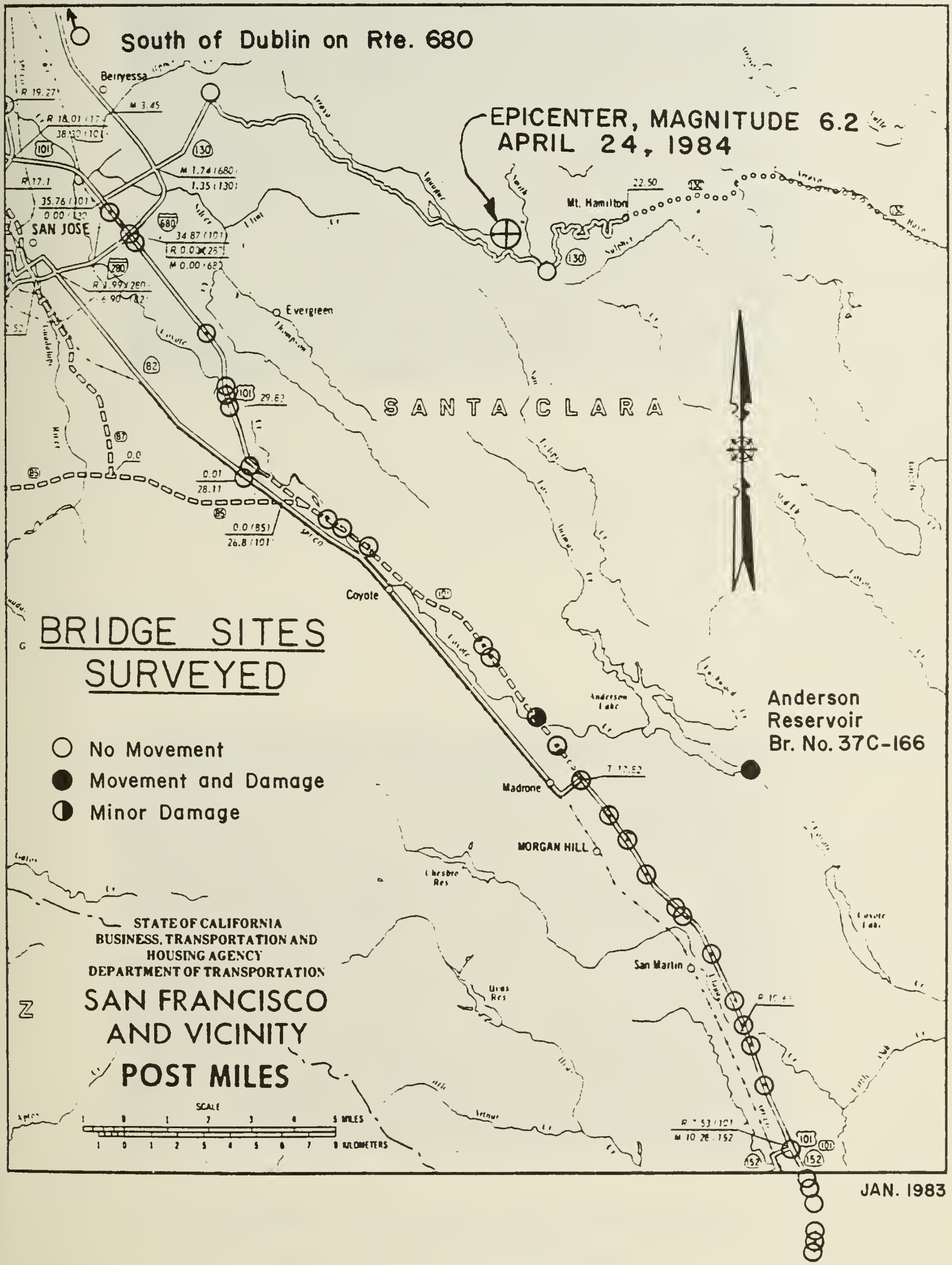
Thirty-seven State Highway bridges on Routes 17, 101, 130, and 680 in Santa Clara and Alameda Counties along with 2 Santa Clara County bridges were investigated.

Major damage: 1 bridge.
Minor damage: 1 bridge.
No damage due to earthquake: 37 bridges.

ACKNOWLEDGMENTS

The authors would like to thank Ray Zelinski, James H. Gates and the Caltrans staff for their help in preparation of this report.

FIGURE 1



South of Dublin on Rte. 680
EPICENTER, MAGNITUDE 6.2
APRIL 24, 1984
Berryessa
Mt. Hamilton
SAN JOSE
Evergreen
SANTA CLARA
Coyote
BRIDGE SITES SURVEYED
No Movement
Movement and Damage
Minor Damage
Anderson Reservoir
Br. No. 37C-166
Madrone
MORGAN HILL
San Martin
STATE OF CALIFORNIA
BUSINESS, TRANSPORTATION AND HOUSING AGENCY
DEPARTMENT OF TRANSPORTATION
SAN FRANCISCO AND VICINITY
POST MILES
SCALE
MILES
KILOMETERS
JAN. 1983

Abut. 6 Abut. 1

PHOTO 1 County bridge over Anderson Reservoir.
Br. No. 37C-166

PHOTO 2 Rockslide at north end of bridge near
Abutment 6. Br. No. 37C-166

PHOTO 3 Transverse cable restrainers at Pier 5. Br. No. 37C-166

PHOTO 4 Restrainer unit at Abutment 6. Br. No. 37C-166

PHOTO 5 Anchor bolts sheared off at Abutment 1. Br. No. 37C-166

PHOTO 6 Pier 2 knocked out of plumb. Br. No. 37C-166

PHOTO 7 End slab span at Abutment 1 restrains timber deck movement. Br. No. 37C-166

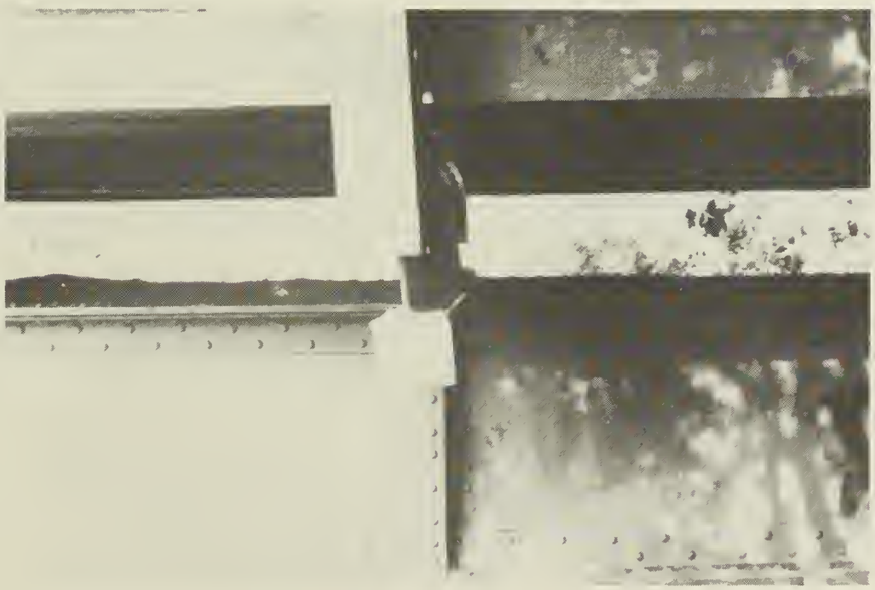


PHOTO 8 Transverse beams pushed out of plumb. Br. No. 37C-166

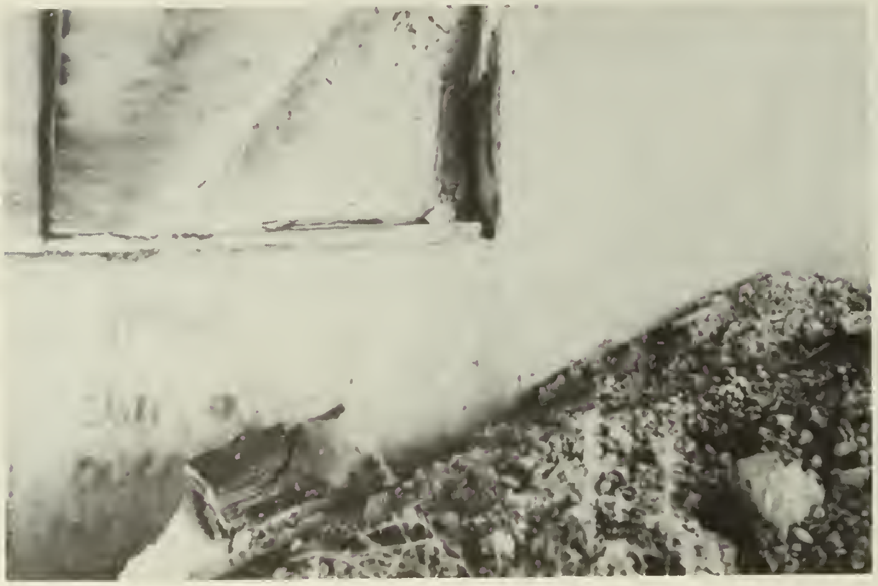


PHOTO 9 Coyote Creek Bridge, Br. No. 37-349L
End diaphragm spall at south abutment.

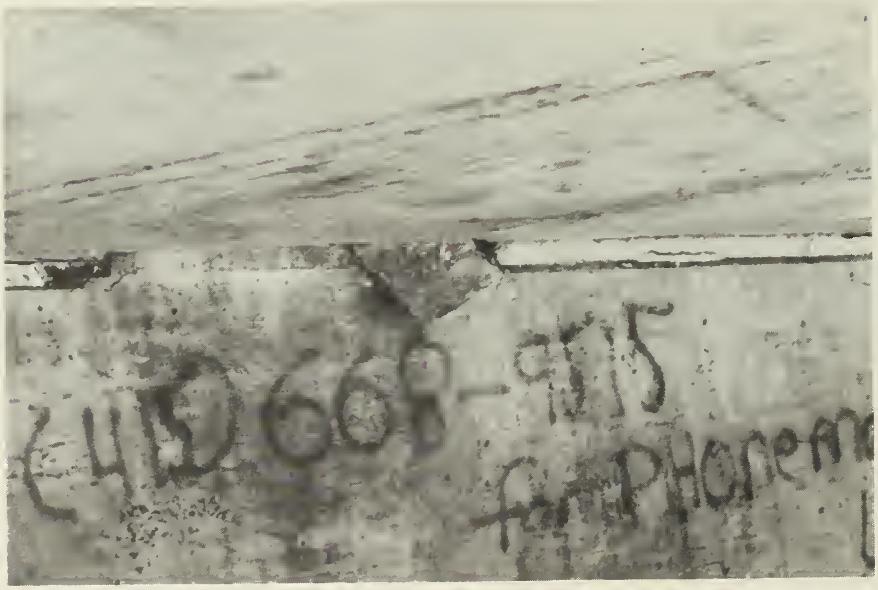


PHOTO 10 Coyote Creek Bridge, Br. No. 37-349L
Interior key spall at south abutment.

Section II

EMERGENCY RESPONSE

STATE EMERGENCY SERVICES RESPONSE
TO THE 1984 MORGAN HILL EARTHQUAKE

by

Jane Victoria Hindmarsh [1]

INTRODUCTION

On Tuesday, April 24, 1984 at 1:16 p.m. (PDT) an earthquake occurred 12 miles southeast of San Jose. Shaking was felt from San Luis Obispo to Sonora to Minden, Nevada. The National Earthquake Information Service reported the magnitude as 6.2R. Damage was centered in Morgan Hill and the surrounding area of Santa Clara County. The affected area is principally a bedroom community to San Jose. There is some light industry, and agriculture, largely flowers, row crops and prunes. The median annual income is $28,000 in a population of approximately 19,000.

Despite the intensity of ground-shaking, there were no deaths. Twenty-seven persons were treated for injuries. Total losses were estimated at $8.0 million. Cities, County, and State emergency response systems activated immediately, handling the situation effectively and efficiently. We particularly acknowledge the dedication of the staffs at Morgan Hill and San Jose Cities and Santa Clara County. Since they are more familiar with details at their level, this report will concentrate on State response activities.

ACTIVATION OF THE STATE OPERATIONS CENTER

Located in the California Office of Emergency Services is a mapboard of the state, studded with lights and bells. Linked electronically to seismographic recording stations, this board is part of an Earthquake Alert Telemetry System. When the lights and bells are activated by seismic activity at their corresponding stations, their pattern and duration provide OES with an immediate estimate of an earthquake's epicenter and magnitude.

On April 24, the on-duty Warning Controller was on the telephone with Santa Clara County Operations Center discussing a hazardous waste spill. Suddenly, the county staff person announced they were having an earthquake. As he spoke, lights on the mapboard began blinking in front of the Warning Controller. Following standard operating procedures, he immediately notified other staff members, and performed necessary emergency actions from the telecommunications center until the State Operations Center (SOC) opened at 1:26 p.m.

The staff of OES Region II, located in Pleasant Hill (Contra Costa County) felt the temblor and within minutes was coordinating between the SOC and the affected counties.

By radio, OES asked counties to report if they felt the quake, and if there was known damage. Based on the response, paying particular attention to those areas having problems communicating information, OES telecommunications advised the SOC that the most likely site of worst damage was Morgan Hill.

[1] State of California, Office of Emergency Services

Following well-practiced procedures, state agencies with a role in earthquake response were alerted. Included were: California National Guard, California Highway Patrol, Emergency Medical Services Authority, Department of Social Services, Caltrans, Department of Water Resources, Department of Forestry, Division of Mines and Geology, California Conservation Corps, Public Utilities Commission, Department of Food and Agriculture, and Department of General Services. SOC staff also notified the Governor's Office, Seismic Safety Commission, Federal Emergency Management Agency, and the American Red Cross.

Because initial reports indicated damage to be slight, agencies were not asked to send liaison to the SOC immediately, but to stand by in case that became necessary. Following an existing agreement and procedures between OES and the Structural Engineers Association of California, volunteer structural engineers made themselves available for safety inspections.

SITUATION

Damage was scattered throughout the Bay Region. In San Francisco, a piece of cornice fell from a building on Pacific Street, and windows shattered at the Western Merchandise Mart on Market Street. San Francisco International Airport reported some ceiling tiles fell in one of their buildings. In San Jose, the multistory city and county administration building was evacuated. There were rock slides on roads around Mt. Hamilton; and at Lick Observatory, a telescope lost power when the quake broke a control wire. The Bay Area Rapid Transit System was shut down for approximately ten minutes. There were broken windows in the downtown section of Hollister and a smoking transformer was reported west of town. There was damage at the Los Banos substation of Pacific Gas and Electric. Many areas experienced temporary power outages. Telephone service was disrupted by overloading as people tried to call into and within the area. There were a number of earthquake related fires. There was significant damage to prisoner barracks at Elmwood Minimum Security Center, Milpitas.

Hardest hit was Morgan Hill, where hundreds of homes and dozens of businesses sustained some degree of damage.

By far the report causing the most concern was that describing damage at Anderson Dam. If the dam's structural integrity were threatened, the entire area between New Almaden and Gilroy would be inundated, endangering lives and property. Morgan Hill would be hit by water within twenty minutes.

STATE RESPONSE ACTIVITIES

From the first notification of potential problems at Anderson Dam at 2:15 p.m., the SOC maintained close coordination with State Division of Dam Safety and Santa Clara County Water District. Following their emergency procedures, Water District staff automatically reported to specified sites to investigate for damage. The District had status reports on all their dams within an hour and a half. In case evacuation was necessary, the law enforcement mutual aid system was alerted; the SOC and OES Region II prepared to assist the County with appropriate resources. At 4:30 p.m. the SOC was notified that Anderson

Dam had a crack in the roadway surface, but there was no immediate threat to the dam. The next day, DWR and the District performed further analysis and determined the dam structure to be unaffected by the roadway surface damage.

Emergency Medical Services Authority polled hospitals and clinics to determine medical needs arising from the earthquake. Wheeler Clinic in Morgan Hill reported treating two injured persons. In Gilroy, Wheeler Hospital treated 24 persons; one was admitted for observation.

At Elmwood Minimum Security Center, inmates were safely evacuated from damaged barracks. Due to the minimal impact of this earthquake on their resources, the Sheriff's Office was able to commit the necessary time and personnel to accomplish evacuation and relocation without assistance from other law enforcement mutual aid personnel.

PG&E reported damage to power circuit breakers at Los Banos and Metcalf. Until repaired, DWR stopped pumping operations on the California aqueduct south of Los Banos. CNG conducted a flyover of the aqueduct to investigate for possible damage. Ground investigations were carried out by DWR, but no problems were identified.

Damage to public facilities was spotty throughout the region. Volunteer structural engineers were requested by the County to assist the Chief Building Inspector of Morgan Hill. Over a four-day period, 10 engineers spent 12 man-days inspecting 140 residential and 80 business structures.

Department of Housing and Community Development did a preliminary inspection of the area's mobile home parks on April 25. They found 49 homes off their piers and one structure fire caused by toppling of the water heater which was located in the same compartment as the furnace. Of six parks in the Morgan Hill area, one (with 173 homes) had gas turned off due to damaged lines.

Office of the State Architect did an immediate investigation of schools and other public buildings. Most of the damage at school sites was nonstructural, i.e., broken light fixtures, falling bookcases, and the like. Of the children injured at the school, one was injured when unbraced library bookshelves fell; one was struck by a plaster-of-Paris art project; and three were hurt as they dived under their desks.

Fire mutual aid system constantly monitored the situation. There were 81 earthquake-related fire department responses, of which five were significant structural fires. Seven were confirmed gas leaks without flame. In Morgan Hill there were three minor fires due to faulty pilot lights which relighted automatically. A four-alarm fire that erupted after a fuel line broke destroyed three stores in a downtown shopping center in San Jose. Damage estimate was $1 million.

Department of Forestry dispatched a unit to the Anderson Lake area because of reports that some houses were off their foundations, and possibility of gas leaks. CDF responded to numerous calls from citizens in the Morgan Hill/Gilroy area requesting advice regarding actual or suspected gas leaks.

Department of Mental Health worked with the County and volunteer agencies to provide crisis counseling to people in the impacted area.

California Division of Mines and Geology sent four teams into the area to observe seismic phenomena, monitor aftershocks, and, if possible and necessary, advise the SOC of additional hazards.

OES Utilities staff coordinated between the affected utilities companies and the SOC. It was estimated that as many as 50,000 households were without power after the quake. By 5:30 p.m., all but 1,000 customers, mostly in Morgan Hill and North San Jose, had their service restored. Some water mains also had damage. Most were repaired within a few hours; however, parts of the area were without water for a couple of days.

American Red Cross notified Department of Social Services that they had opened a mass care center at Friendly Inn, a Morgan Hill City Parks Senior Citizens Center. No one made use of this resource.

Immediately after the earthquake, Caltrans conducted a survey of the freeways throughout the area, but found only minor damage. On April 25, a more detailed inspection was made of freeway structures in Santa Clara County.

The media was well represented at the SOC, but did not materially interfere. However, there was a problem in Santa Clara County with media entering the county building during the evacuation.

OES Region II closed their operations center at 7:40 p.m.; the SOC closed at 8:00 p.m. OES's Warning Controller and Region II's 24-hour answering service had specific instructions regarding reactivation should that become necessary from aftershocks or other causes.

DECLARATIONS

The City of Morgan Hill proclaimed a local emergency shortly after the earthquake occurred on April 24. Santa Clara County proclaimed for the entire county at 3:05 p.m.. On the afternoon of April 25, within an hour of receiving the formal requests from Santa Clara County and the City of Morgan Hill, the Governor proclaimed a State of Emergency for the County.

By the second day, the City of Morgan Hill realized that most of the damages were private sector (i.e., homes, businesses). Since the Governor's proclamation alone provides very little direct aid to victims, the City asked the Governor to request a Presidential Declaration of Major Disaster.

On April 26 representatives of state and federal agencies, in conjunction with local government and voluntary relief agencies, conducted an on-site assessment in Santa Clara County. Assessment identified 522 homes damaged, with estimated dollar loss of structures and contents of $5.4 million. The 43 damaged businesses had an estimated loss of $1.7 million. The assessment team determined the only qualifying program to benefit victims was that provided by Small Business Administration (SBA).

On April 27, the OES Director requested a declaration from the SBA Regional Director. Red Cross assisted in the field survey. On May 2, the SBA declaration was made for Santa Clara and Santa Cruz Counties, and an onsite office established on May 4.

Realizing that the area would be unlikely to qualify for a Presidential declaration, the American Red Cross and Salvation Army set up a community meeting for April 26 to inform victims of services, programs and aid available from those organizations and other members of National Voluntary Organizations Active in Disasters.

Public real property damage was confirmed at $365,000, of which $208,200 pertained to Federal Aid System roads and $30,000 to Unified School District facilities. These repairs will be covered under specific programs, leaving $127,000 to be borne by local government, well below the levels which would justify a request for a Presidential declaration. Since the initial survey, an additional $484,000 has been identified, largely in the areas of overtime and accounting costs. Upon verification, eligible items will be reimbursed, in whole or in part, under terms of the Natural Disaster Assistance Act.

As of August 15, 1984, damages were confirmed as follows:

HOMES/MOBILEHOMES

		Structure	Contents	Total
Destroyed	5			
Major damage	49			
Minor damage	469			
Total	522	$2,914,700	$2,525,800	$5,440,500

BUSINESSES

Destroyed:	5			
Major damage:	3			
Minor damage:	35			
Total:	43	$1,105,000	$ 650,000	1,755,000

Total Private Property Damages	$7,195,500
Total Public Property Damages	849,000
Total Damages	$8,044,500

SIGNIFICANT ISSUES

Since staff for disaster operations have other responsibilities during "normal" times, there can be great difficulty in dealing with the disaster response and the normal role simultaneously. Ideally, this would not be necessary, but in reality there are some programs which cannot stop despite disaster. For instance, Department of Social Services and County Welfare offices must maintain the welfare program, as well as manage specific emergency relief functions, such as Individual and Family Grant Program and emergency food stamps. At the county level, the County Executive Officer went to the Emergency Operations Center to handle the disaster, and the Assistant CEO stayed at the County Building to handle administrative problems. This worked well and will become a standard procedure in their formal plan.

The CHP initial aerial surveillance was very helpful to the County in assessing the situation. However, the numbers of media helicopters and sightseeing aircraft competing for airspace posed a safety hazard in completing aerial inspections. The Federal Aviation Administration should be requested, very early into the disaster, to close airspace over the impacted area ro reduce the risk of a midair collision.

In addition to hazards created by falling bookshelves and other fixtures, the County Building developed cracks in the walls which required assessment by structural engineers to determine safety issues. However, it was initially unclear as to who had authority to evacuate the building. Every building owner/manager should designate who, onsite, has responsibility to make the decision to evacuate. If there are several buildings in a complex, someone in each building should be designated to make decisions.

Immediate attempts to restore utilities sometimes caused a fire. Automatic timers can cause fires. For example, a floodlight fell over, but its automatic timer switched on, causing a grass fire.

A myriad of independent agencies receive, from their own sources, information and data relating to the disaster. That information and data are useful only insofar as they are shared with the Emergency Operating Center. Information not provided in a timely manner can interfere, frustrate, duplicate and otherwise undermine response efforts.

SUMMARY

As we plan for the catastrophic earthquake that some day will strike California, Morgan Hill reminds us that we must be ever vigilant to prepare for that moderate quake that can strike anywhere in our State. Any disaster is a catastrophe to the community it hits.

FIRE-RELATED ASPECTS OF 24 APRIL 1984 MORGAN HILL EARTHQUAKE

by

Charles Scawthorn*, Gilles Bureau*,
Craig Jessup** and Robert Delgado***

ABSTRACT

Fire following the 24 April 1984 Morgan Hill earthquake (M 6.2) was a primary cause of damage in the cities of Morgan Hill and San Jose, California. Delays in telephone dial tones, perceived as telephone outages, resulted in delayed reports of structural fires to fire departments. One fire at a shopping center in San Jose was the single largest loss in the earthquake, totaling approximately $1 million. Multiple non-fire specific incidents which fire departments were called to respond to, such as gas investigations, structural damage checks, downed power wires and medical aid, placed additional heavy demand on limited resources.

INTRODUCTION AND FIRE-RELATED EVENTS

Although the Morgan Hill earthquake of 24 April 1984 and resulting damage were of only moderate magnitude, the several fires and fire-related operations related to the earthquake contain significant lessons that will be of paramount importance in a larger earthquake. In the six hours that followed the earthquake, which occurred at 1:15 PM (or 1315) PST, a total of 79 earthquake-related confirmed incidents were reported for the Morgan Hill Fire Department (32), San Jose Fire Department (29), the California Division of Forestry (4), and Gilroy and the area south of Morgan Hill (14). Of these incidents three were fires which resulted in major structural damage. Other incidents included gas leaks without fire, chemical spills, and structural damage investigations. This chapter discusses these fires and related aspects, focusing on the cities of Morgan Hill and San Jose, which were the communities most directly affected by the earthquake.

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** Morgan Hill Fire Department, Morgan Hill, CA 95037
*** San Jose Fire Department, San Jose, CA 95110

Events in Morgan Hill

The City of Morgan Hill (population 18,000) has a fire department consisting of 14 paid call firemen and 30 volunteers. Equipment includes 1500 gpm and 1250 gpm engines, carrying 500 gallon tanks and located one at each of the two fire stations in Morgan Hill, as well as a 750 gpm reserve engine (300 gallon tank) and a quick attack vehicle capable of pumping 250 gpm and carrying a 500 gallon tank. Also located at the south end of Morgan Hill is a California Division of Forestry (CDF) station with three engines, equipped for brush fires.

Almost immediately after the earthquake occurred at 1315, engine 132 (E-132) noticed smoke and responded to a small grass fire beneath a power pole. The fire, which was spreading at a slow rate, was readily extinguished. Subsequent events included (in chronological order):

- 1325: a medical call to Wheeler Hospital clinic, which did not actually involve a medical emergency. Because files and supplies were in substantial disarray ("all over"), a structural check was performed.

- 1329: investigation of a structural collapse at 2nd and Monterey Sts, which actually only involved some bricks in the street, from a parapet. This determination was made by the MHFD fire chief, who subsequently established his incident command post at this location, which is in the center of Morgan Hill. He also directed E-130 to a gas investigation in this vicinity, which resulted in gas and power being cut off for a city block. Subsequent investigation revealed wiring in an electric box had burnt.

- 1333: grass fire involving about a half acre, at 800 Tennant Ave.

- 1333-1358: four additional incidents, involving medical aid, (hysterical persons), vehicular accidents, false report of a structural collapse.

- 1347: report of a structural collapse in Jackson Oaks area. E-132, responding to a medical aid call, observed multiple single family dwellings with varying degrees of damage, from minor to partial collapse (reported elsewhere in this volume), as well as observed breaks in water mains, residents in street with minor injuries and reports of trapped occupants. Residents had already turned off about 30% of the residential gas service. E-132 completed cut-off of all gas and electric service to an area comprising

approximately 30 residences along Oak Ridge Ct. and vicinity, and performed a preliminary reconnaissance, searching all homes in the affected area for trapped victims. A first aid station was established, the area cordoned off, an incident command post established and operations involving CDF, MHPD, CHP and Santa Clara Sheriff's Office personnel were coordinated. Due to water main breakage, an area comprising approximately 500 homes was without water, so that outbreak of fire was a serious concern. As darkness ensued, some candles were observed in use, and it was recommended to the Building Department that victims in the affected area not remain in their homes until the structures had been cleared by the Building Department, as structurally safe. As a consequence, most of the residents in these approximately 30 dwellings spent the night elsewhere. As the afternoon wore on, the situation developed complexities, including:

* 1530:school buses released returning school children, which made enforcement of the cordon more difficult,

* Ten to fifteen helicopters and fixed-wing aircraft in the vicinity, sometimes flying less than 500 ft. above the ground. One helicopter landed in the cordoned-off area, and attempted to discharge what appeared to be journalists, but left with the personnel after a warning from MHFD personnel. At about 1610 there was observed what appeared to be a near-miss overhead, involving a helicopter and a fixed-wing aircraft. At 1615, following a second request by MHFD (the first request may not have been received), FAA cleared a five mile radius airspace.

* General Telephone set up three emergency telephones in the area within several hours, two for use by residents and one for use by MHFD. This was a grateful consideration, as it permitted MHFD personnel to confirm the well-being of their families.

* Within a hour or two, there were about 30 to 50 media personnel in the area.

MHFD was able to leave the scene at about 1730.

- 1347-1513: five gas investigations (usual procedure was to investigate, and turn off gas pending utility company investigation) and two medical aid (hysteria, and a broken ankle).

- 1513: structural fire at 31 Chestnut St., involving a double

wide mobile home, about half involved upon arrival of E-131. Probable cause was a natural gas leak in the water heater enclosure. Total loss was estimated to be about 50%, or $40,000.

- 1513-1752: four gas investigations (one of which was actually a chemical spill at a residence, involving malathion. This was subsequently cleaned up by the residents, not using procedures advised by MHFD. Several days later, odor of the pesticide persisted throughout the house, and one family member reported nausea), one electrical malfunction (broken insulator on power pole), one medical aid (possible broken right arm, sustained falling from bicycle), and two structural damage investigations (damage determined to be mainly non-structural).

- 1836: small fire on roof at 17455 Monterey Rd., caused by a flood light knocked down onto the roof at the time of the earthquake, being turned on by a automatic timer device, subsequently overheating and igniting the roof covering. This fire was quickly reported and rapidly extinguished.

- remainder of 24 April: five more gas investigations, three of which actually involved possible leaking gas, while one was a spill of malathion in a garage, and one was a spill of malathion and paint at a hardware store. Three other incidents involving structural investigations.

- 25-28 April: two minor leaks of gas, one incident involving broken water pipes, one incident involving minor spill of household pesticide. One minor residential fire due to chimney damaged by the earthquake. One other fire possibly due to the earthquake (involved a mobile home, in which gas service had been restored one hour prior to the fire).

In summary, on 24 April, in approximately nine hours following the earthquake, MHFD responded to:

- 2 structural fires

- 2 grass fires

- 12 gas investigations (3 actually chemical-related)

- 7 medical aid calls

- 6 structural damage investigations, and

- 6 other (vehicle accidents, alarm sounding, etc)

for a total of 35 incidents, compared with an average of about 1.9 incidents per day.

Events in San Jose

San Jose Fire Department, serving a 206 sq. mile fire district with a population of about 730,000, consists of 680 personnel (174 per shift) in 28 fire stations and four district headquarters. Equipment includes 28 engines (usually 1200 or 1500 gpm), 10 ladder trucks, 10 light units, 6 hose wagons, 6 patrol tankers (usually used in wild lands), 3 tankers, a hazardous incident unit and several rescue units. The average number of incidents for a Tuesday, is approximately 3.5 to 4.5 incidents per hour. On Tuesday, 24 April, SJFD handled:

1300-1400:	23	incidents
1400-1500:	21	"
1500-1600:	4	"
1600-1700:	9	"
1700-1800:	5	"

In the first four hours, 29 confirmed earthquake-related calls were broken down by type of call as follows:

gas investigations	8
wires down	5
structure fires	4
alarm sounding	3
transformer leak	2
service calls	4
spills	1
grass fire	1
evacuation	1

The evacuation incident was the evacuation of the Santa Clara County Administration Building. Many of the SJFD responding incidents were similar in nature to those discussed above for Morgan Hill, and thus will not be discussed in detail here (see also Ref. 1 for a detailed description of the San Jose EOC activities in the hours following the earthquake).

The largest fire occurred at 1331, in a shopping complex at Santa Teresa and Cottle Aves, in the southern portion of San Jose. There appears to have been a delay in reporting this fire, due to telephone dial tone delays, and the report is stated to have been received from a citizen who drove to the nearest fire station. The fire was in a one story wood framed, woodshake

roofed building approximately 45 x 125 feet, containing three businesses: an auto parts store, an aquarium business, and a video business.

The fire appears to have been caused by a broken gas connection to the heating element of a hot solvent parts cleaning device, in the auto parts store. Upon arrival SJFD E-12 noticed the auto parts store filled with smoke and attacked the fire with two 1-1/2" lines, meanwhile laying a 3" supply line to a nearby hydrant. However, flashover occurred at about this point, and the fire spread rapidly through the attic area to the other two businesses in the building. Second and third alarms were turned in, although radio traffic from the large number of on-going incidents may have slightly delayed the second alarm report.

Eventually, four engines and two trucks, using approximately 50,000 gallons over a 60 minute period, succeeded in containing the fire to the one building. This was despite the neighboring building being also a wood shake roof building of similar construction, separated by an eave-to-eave distance of only about six feet, and a wind speed of about 12 to 16 mph (recorded in downtown San Jose, P. Belchamber, Santa Clara County OES, personal communication). Total loss was estimated at $500,000 for the structure and $415,000 for the contents.

Dwellings on Nature Dr. directly to the rear of the shopping center fire sustained some smoke damage to structure and contents. Additionally, a wood shake roof on a dwelling approximately one block downwind (6151 Cottle Rd.) was ignited by flying brands. This was reported by a passerby by telephone to fire communication, who notified "Cottle Command" (ie, the incident commander), who dispatched an engine which extinguished the fire. Total damage was confined to approximately a 10 x 10 ft. roof area.

Three other fires were responded to by SJFD within the first five hours following the earthquake. These were:

- 1336: an attic fire in a commercial laundry, caused by an electrical short in conduit igniting cotton lint. Damage was minimal, and the fire extinguished prior to arrival of SJFD.

- 1354: a fire at 67 Mt. Hamilton Rd, involving a mobile home. Due to phones "inoperable", the fire was reported by a neighbor traveling to the fire station. When SJFD E-2, E-19 and Tanker No. 2 responded the home was fully involved, and they used 2-1/2" lines to attack and extinguish the fire. It was determined that the earthquake had snapped a power line which fell onto the dwelling roof, arcing through

the roof covering and igniting structural members and contents. The only person home was a ten year old boy, who ran to neighbors for assistance, who in turn drove to the fire station. Note that 41 minutes had elapsed from the time of the earthquake (and presumably the power line falling onto the roof) until SJFD received the report. Total damage was estimated to be $50,000 structure and $20,000 contents.

- 1542: 3042 Driftwood, Apt. 32. A vent of a water heater dislodged, causing ceiling to overheat and begin smoking.

San Jose Fire Department statistics indicate that at 1410 (ie, 55 minutes after the earthquake), 52 of the 72 fire units (ie, engines, trucks, etc.) were committed to this emergency. This left only 20 remaining units for the 206 square miles district. Within another hour, SJFD had approximately 50 units available.

Other, fire-related, occurrences included:

- power to the SJFD communications center was interrupted for approximately three minutes after the earthquake. SJFD uses computer-aided dispatching, and the computer "crashed" during these three minutes, necessitating manual dispatching. However, it should be noted that computer "crashes" are an occasional occurrence, and manual dispatching is feasible and effective.

- due to confusion and a false fire alarm in San Jose City Hall, the City Hall and EOC were evacuated, although the EOC was re-entered and started-up within several minutes.

- delays (approximately 30 seconds) in getting a dial tone at the EOC resulted in the incorrect assumption that the "telephones were out".

- at 1435, with five "wires down" emergencies, two working structure fires, two grass fires and fire units "running from emergency to emergency", call-back of off-duty personnel began. Within 12 minutes, six off-duty personnel were enroute.

- at 1440 it was decided to dispatch an assistant fire chief to San Jose airport for helicopter reconnaissance. Reports began to be received at about 1500.

OBSERVATIONS AND ISSUES

This section presents some observations and issues that have emerged from the experience in this earthquake:

- The Morgan Hill and San Jose Fire Departments functioned extremely well, coordinating their efforts, establishing emergency command centers and procedures.

- Communications were highlighted as an extremely necessary but vulnerable link in the firefighting effort. Reports of fires are too dependent on the telephone system. San Jose had a pull-box system until several years ago, when it was removed, and now relies solely on the telephone system for fire reports. Note that both major fires in San Jose were reported by citizens driving to fire stations. Fortunately, the stations were manned at the time. Had the units been out of the station at an emergency, the delays would have increased even more, causing small fires to become larger. In a larger earthquake, some damage to telephone equipment should be planned for. Immediately following the earthquake, Pacific Telephone experienced an increase of 84% over usual telephone use. The system is designed to handle this overload by causing a slowdown in response (delays in receiving a dial tone of about 30 seconds were experienced in this earthquake), which can be perceived as "the phones are out". The public and emergency officials must be educated to expect less than ordinary telephone response in a major earthquake, and to be prepared with alternative communication methods (eg, the public should know the location of the nearest fire station; emergency officials should have in place standing automatic damage reconnaissance plans, involving aerial reconnaissance, block-by-block "windshield surveys" or other methods of quickly assessing the size of the problem, in order to optimally allocate resources).

- The San Jose EOC was temporarily evacuated. Back-up EOC's should be provided for, without automatic referral if the prime EOC is designated as not functional.

- A significant portion of the incident load in this earthquake was not specifically fire-related (eg, gas investigations, structural damage checks, medical aid calls). Although these are part of the normal modern fireman's job, in an earthquake these tasks overburden limited fire department resources, which should be first reserved for firefighting. Efforts should be made to coordinate with utility companies, building departments,

structural engineers, medical resources etc to automatically assume some of these tasks in an emergency. Dispatching of this supplemental aid via the EOC might be considered, although this would require considerable planning and exercising.

Relations and coordination with journalists and other media personnel need improving. Their legitimate requirements for information are sometimes burdensome, particularly for public information officers not experienced in large-scale disasters. The problem of low-flying aircraft, presumably mostly media-employed, has been especially worrisome to fire officials in this and past disasters (eg, the 2 May 1983 Coalinga earthquake). The media can actually prove of benefit to emergency operations if cooperation is planned for and agreed upon. For example, the rapid damage reconnaissance procedures called for above could be performed in part by media aircraft, which are video equipped and are experienced in aerial reconnaissance. The role of the media in a major disaster requires further examination, both by public officials and by the profession itself.

Restoration of utilities (gas and electricity) can result in delayed fires, at the time of the service restoration. This can be hours to days after the initial disaster. Restoration needs careful thought as to how and when to reconnect an area. Consideration might be given to not restoring service before individuals are present in every structure (with public officials authorized to enter those structures whose owners are not available) in order to check for fire or gas leaks, and for standby fire units to be in place in the area at the time of utility restoration.

Although no fire occurred (probably thanks to the action of several responsible citizens who systematically initiated shutting off of residential gas service in the neighborhood), approximately five hundred homes in the Jackson Oaks area of Morgan Hill were isolated for 45 minutes after the earthquake (no damage was reported until discovered by a fire unit on an injury call). The area was deprived of water for several days due to broken water mains, with a resulting major fire hazard. MHFD did station a water tank truck at the scene, which would be sufficient for a small fire. In future earthquake disasters, similar situations will likely arise.

As noted above, the SJFD dispatching center computer temporarily "crashed", due to a power outage. Emergency service operations should not rely on computers without

reliable back-up power. Operations should be regularly exercised with computers "down".

CONCLUSION

Although the Morgan Hill earthquake was a relatively small affair, causing little structural damage, it resulted in several structural fires, which were the primary agent of loss in this earthquake. Fire departments experienced the greatest demand for service in the memory of senior staff members. Although able to cope at all times in this event, it can be seen that fire department capacity would be exceeded in an earthquake of only moderately higher intensity. Several observations and issues were identified above which might aid fire departments in increasing capability or decreasing work load in a future earthquake.

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Section III

GEOLOGIC AND GEOPHYSICAL INVESTIGATIONS

THE CALAVERAS FAULT ZONE OF CALIFORNIA,
AN ACTIVE PLATE BOUNDARY ELEMENT

by

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ABSTRACT

The Calaveras zone shares interplate motion with the San Andreas and other faults. The zone is 0.1-2.0 km wide, comprising aligned and en echelon faults, splays, and compressional and extensional features. Various segments of the composite zone differ in azimuth by 5°-22° and presumably acquire varying stress. Thrust faults locally parallel the zone and converge with it downward. Pull-aparts may exist, as at Coyote Lake. During its evolution, the youthful fault utilized pre-existing weaknesses, including a lineament marked by 3.6 m.y. old basalt near Gilroy. Northward, it adopted a steepened portion of the Coast Range thrust, causing marked stratigraphic disparity on the two sides, whereas elsewhere stratigraphic differences are minimal. In the Pleistocene, strike-slip near the north end of the zone was partially absorbed by thrusting on faults trending NW to WNW. Today, however, dextral motion jumps from the northern terminus of the Calaveras to the Concord fault. In the southern part of the Calaveras, aseismic slip averages ca. 1.2 cm/yr and geodetic motion is ca. 1.5 cm/yr. Farther NW at Calaveras Reservoir, geodetic motion is only ca. .75 cm/yr, some movement having transferred to the Hayward fault. Creep and much of the seismicity likewise transfer to the Hayward. The Calaveras probably originated about 3.6 mybp, but most of its total slip (16-24 km) could have accrued in the last 2.8 m.y. Incidental vertical slip has been imposed on the fault zone by uplift of the East Bay Hills on one side and part of the Diablo Range on the other side.

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INTRODUCTION

The Calaveras zone, more than 130 km long, is a seismically active member of the family of dextral strike-slip faults which characterize the boundary between the Pacific and North American plates. Its southeasternmost extremity apparently lies close to, and parallel with, the San Andreas south of Hollister, but the fault departs from this trend and swings more northerly through Hollister, continuing to the northwest past Danville. Beyond Danville it becomes less distinct, but various manifestations of the zone may continue to the Straits of Martinez, although this is uncertain. Evidently in the past, part of the strike slip motion of the northern portion was converted to oblique slip or thrusting on faults branching off into the terrane west of the main zone. Possible examples of such faults include the Bolinger, Las Trampas, and Franklin faults (Page, 1982, Fig. 1). Most of the faults just mentioned do not show obvious signs of Holocene activity, perhaps because much of the strike-slip motion of the northern Calaveras zone is now relayed to the Concord fault in a right-hand stepover (Ellsworth and others, 1982).

GEOLOGIC CONTEXT

Principal Rock Assemblages

The rocks of the region (Fig. 1) comprise three main groups: (1) the Franciscan Complex, a highly deformed heterogeneous subduction zone assemblage of (mainly) Upper Jurassic and Cretaceous rocks; (2) the Great Valley forearc basin sequence of moderately deformed clastic sedimentary rocks of about the same age as the Franciscan; they rest on ophiolite, of which only fragments are preserved; and, (3) a partial cover of folded Cenozoic sedimentary rocks. The Franciscan and parts of the Great Valley sequence probably underlie the entire East Bay region.

The Neogene rocks are less deformed and differ markedly from the Mesozoic rocks in character and mode of origin. Some are shelf-type sandstones and mudstones. Parts of the middle Miocene section consist of basin deposits of siliceous shale, porcelanite, and chert. In the vicinity of the Calaveras fault zone, sediments of upper Miocene ($\leq$ 10 m.y.), and Quaternary age are largely or entirely nonmarine, reflecting emergence which still persists in much of the region. These nonmarine deposits have been discussed by Wagner (1978) and Creely and others (1982), and have been further interpreted by Graham and others (1984). According to these sources, the sediments (with local volcanics) reflect the transition from plate convergence to transform tectonics. Nonmarine sediments formerly equated with the Orinda Formation occur on both sides of the Calaveras zone east of the Berkeley Hills, and parts are at least

as young as Pliocene; a tuff layer about 1500m above the base of the section is considered to be 4.0 $\pm$ 1.0 m.y. (Sarna-Wojcicki, 1976). The Livermore Gravels are proably only 5 to 0.6 $\pm$ 0.1 m.y. old (Herd and Brabb, 1980). Southeast of Niles and thence to Gilroy, upper Cenozoic nonmarine sediments commonly called the Santa Clara Formation are probably about the same age as the Livermore Gravels. Between Morgan Hill and Gilroy, the Santa Clara encloses basalt flows dated at 3.6 $\pm$ 0.1 m.y. by G.H. Curtis (in Sarna-Wojcicki, 1976, and Dibblee, 1973). The foregoing late Cenozoic formations are folded and are offset by the Calaveras and other faults. The recency of the deformation is impressive.

Diablo Antiform

The Franciscan core of the Diablo antiform is exposed along the northeast side of the fault zone (Fig. 1), but on the southwest side the Franciscan is largely hidden by overlying formations. This creates a false impression of large displacement, but in fact the west limb of the antiform just happens to coincide with the Calaveras fault. Great Valley sequence sediments, with remnants of underlying ophiolite, once formed a tectonic cover over the Franciscan core of the antiform. The Coast Range thrust (Bailey and others, 1970) separated the cover from the core. As the antiform grew, its limbs (containing the thrust) steepened, and parts of the Coast Range thrust were converted to dip-slip shears such as the Madrone Springs fault east of Morgan Hill and Gilroy. These successor faults, like the ancestral Coast Range thrust, separate the Franciscan from adjacent Great Valley rocks. Probably the Calaveras fault zone was developing at the same time as the antiform, and it found and incorporated the steepened Coast Range thrust/Madrone Springs fault. The "unused" part of the Madrone Springs fault merges with the Calaveras zone at San Felipe Valley.

In the vicinity of the Calaveras Reservoir, Neogene sediments overlap Great Valley rocks on the west side of the Calaveras fault zone, and overlap the Franciscan Complex on the east side of the zone. Since the Neogene rocks themselves are displaced, the evidence for two separate episodes of faulting is clear, as noted by C.F. Tolman in the 1920's and by Vickery (1925). However, I believe that the older displacement was inherited from the Coast Range thrust, and that it existed before the Calaveras fault zone was born.

CONFIGURATION OF THE FAULT ZONE

It is presumed, without proof, that the strike-slip faults of the Calaveras zone are nearly vertical, as this would be mechanically most efficient in an ideal case. However, the zone is not straight, and out-of-line segments may dip less than 90°. Hypocenters of earthquake aftershocks are generally scattered about one or more imaginary subvertical planes (e.g. Lee and others, 1979; Reasenberg and Ellsworth, 1982). It should be noted, however, that thrust faults are associated with the Calaveras fault zone at relatively shallow depths, as discussed farther on.

Where mapped in detail (e.g. Radbruch, 1968; Herd, 1982), the Calaveras zone is seen to consist of numerous "strands" forming a belt tens of meters to more than 500 meters wide (Fig. 2). En echelon patterns can be discerned locally, but commonly there is no such organized arrangement. At least locally, multiple slip surfaces exist at seismogenic depths as well as at the surface; this is shown by planar clusters of hypocenters of aftershocks of the 1979 Coyote Lake earthquake (Reasenberg and Ellsworth, 1982). The surface traces of some strands are nearly straight; others are moderately curved. The strike of individual strands differs as much as 30° from the trend of the zone as a whole, but generally the deviation is much less. In some areas, such as Anderson Lake, splays trend more northerly than the main zone. These may represent Riedel shears (Tchalenko and Ambraseys, 1970; Wilcox and others, 1973); if so, they must slip dextrally. Some individual faults marked by scarps are remarkably short, and where some die out, others have formed nearby.

The surface trace of the zone is angular in plan (Fig. 2). From Hollister to Danville, a distance of 120 km, the zone as a whole trends about N 27° W, but it can be divided into as many as 11 segments which deviate from this direction by 1° to 24°. The arbitrarily chosen segments in Fig. 2 range in length from 3.5 to 28.5 km and in strike from N 3° W to N 43° W. The angles between adjoining segments are 3.5° to 22°. Mavko (1982) suggests that different segments (not necessarily those shown here) acquire different stresses and have different seismic potential because of the geometry of the system and interaction with other, nearby zones. In a dextral system, one would expect that segments deviating clockwise from the main trend would acquire subnormal transverse compressive stress that would perhaps lead to local extension or pull-aparts. Segments deviating counterclockwise would acquire abnormal transverse compressive stress that would impede strike slip and might lead to local uplift or thrusting. At depth, comparable segments, and/or certain angles and discontinuities inappropriate for easy slip, might favor earthquakes generated in the same place repeatedly, as noted for a section of the San Andreas fault by Spieth and Geller (1981) and for the Calaveras fault by Bakun (1980). The Coyote Lake earthquake epicenter of 6 August 1979 is believed to be near a stepover, and is within 5 km of a

14° angle and a possibly slip-resistant segment (i-j in Fig. 2) in the surface trace of the fault zone. Perhaps the configuration of the zone northwest of Coyote Lake explains the unidirectional, southeastward propagation of slip in August, 1979 (Bakun, 1980), although it is unlikely that the configuration of the fault zone at depth is precisely the same as at the surface. Some obstruction in the Calaveras fault zone beneath Halls Valley may have localized the earthquakes of August 29, 1978, May 8, 1979, and April 24, 1984. These three earthquakes (M_L 4.2, M_L 4.5, and M_L 6.1, respectively) occurred within a 12 km-long section of the fault zone.

THRUSTS AND PULL-APARTS

Thrust faults are surprisingly prevalent along and near the Calaveras zone (Fig. 2) and in the region as a whole (Aydin, 1982; Page, 1982; Aydin and Page, in press). In transverse section, the thrusts appear to diverge upward and outward from strike-slip faults, but the angles of inclination, curvature in profile, and maximum depth of these features are unknown. Causes of the thrusts are considered in the references cited above.

A noteworthy belt of probable thrusts associated with the Calaveras zone extends from the vicnity of Gilroy past Morgan hill, as recognized by Dibblee (1974). The surface trace of some of the suspected thrusts lies at the juncture between the floor of Santa Clara Valley and an adjacent foothills ridge that is bounded on the northeast by the Calaveras fault zone. I consider the foothills ridge to be a rootless prism undercut by thrusts. It is clearly a recently uplifted feature, as it consists of weak material such as Plio-Pleistocene sediments, yet it is not deeply incised by canyons except in one or two places. The hillside facing Santa Clara Valley is marked by longitudinal benches and scarps (some ascribable to landsliding) which trend parallel with the contours. Locally ravines and gullies are offset at scarps as though by oblique slip, suggesting the presence of oblique reverse-slip faults within the foothills as well as along their basal margin.

Less extensive thrusts may be localized at angles in the Calaveras fault zone, as near Anderson Lake (Point "i" in Fig. 2B), where several fault traces are markedly arcuate, as though reflecting moderate dips. At Calaveras Reservoir, where no particular angle in the fault zone is evident, there may be thrusts, as Vickery (1925) observed faults dipping 31° to 53° westerly in an excavation at the damsite.

Local extension as well as compression might be expected in a system of discontinuous strike-slip faults (Segall and Pollard, 1980). Pull-aparts involving transverse normal faulting and subsidence of small blocks are believed to exist in several places along the Calaveras fault

zone where strike-slip has probably shifted from one fault segment to another in right-hand stepovers (Aydin and Page, in press). Likely examples are at Coyote Lake (where the south boundary of the basin may be a normal fault scarp), San Felipe Valley, and perhaps Halls Valley and Calaveras Reservoir (Fig. 2B). Most of these postulated examples are not definitive, and no normal faults are exposed.

EVOLUTION OF THE CALAVERAS FAULT ZONE

Inception of Strike Slip

The fault zone is relatively young. This is indicated by its complex, immature configuration, its mild expression in the Hollister Plain, the similarity of Neogene formations on the two sides, and the lack of sedimentary facies indicating ancient disturbances near the fault zone. One can attempt to estimate the duration of strike slip by dividing the supposed total displacement, ca. 20 km, by the present mean annual geodetic movement rate, .75 cm/yr; this gives 2.67 m.y., which is probably a minimum figure. The oldest geologic indicator of a precursor fault zone is the 3.6 m.y. basalt which is apparently restricted to a linear belt along the southwest side of the Calaveras zone from Gilroy to Morgan Hill (Dibblee, 1973 and 1974). As pointed out by D.L. Wagner (1979), the basalt was probably localized along a fracture zone which evolved into the Calaveras fault. This could be analogous to the relation between the Leona Rhyolite and the Hayward fault. The sedimentary record might be expected to show signs of early fault activity. However, J.R. Wagner (1978) in interpreting the sediments, does not mention any syntectonic deposits closely restricted to the vicinity of the fault. He did find signs of folding commencing before 5.2 mybp west of the fault zone and after 4 mybp east of it. Both folding and faulting have affected sediments of the latter age.

From the foregoing clues, I conclude that strike-slip faulting began along the Calaveras zone in the Pliocene, most probably about 3.6 mybp.

Growth by Incorporation of Existing Fractures

There are indications that the Calaveras fault zone did not come to life as a pristine, through-going fault, but instead developed by linkage of new and old fractures. The segment of the zone which crosses Hollister Plain differs markedly from the rest with respect to orientation and geomorphic aspect, and it joins the next segment near San Felipe Lake at a small, but sharp, angle. Probably the Hollister Plain segment formed quasi-independently and propagated into a pre-existing fault, which it adopted. More obviously, the evolving Calaveras zone

found the Madrone Springs fault, a steep modification of the Coast Range thrust, and incorporated it. Perhaps many of the angles in the surface trace of the fault zone represent the linkage of pre-existing fractures to form an integrated system. However, some of the oblique segments may have originated as Riedel shears in the early history of the zone, as in the experiments of Tchalenko and Ambraseys (1970). Probably the fault zone is still in an evolutionary stage of development that will eventually lead to a more efficient (less angular) system. This will require new fractures cutting across undesirable angles. Crittenden (1951) pointed out a geologically recent "shortcut" between Los Buellis Hills and Halls Valley, east of San Jose, and Rogers (1973) postulated cyclic distortion and shortcutting of fault segments.

TOTAL DISPLACEMENT

Vickery (1925) estimated displacement along the Calaveras zone by measuring the strike separation of the base of the Briones Sandstone (upper Miocene) and the separation of a lower Miocene molluscan horizon. Three different measurements gave 19.2 km, 19.2 km, and 20.8 km. He also noted the presumed separation, 14.4 km, of Pliocene (?) rhyolite, but did not specify the location. I know only two occurrences of rhyolite which Vickery might have used; both are shown by Hall (1958). They are dikes in a quarry south of Dublin and in the Welch Creek area, 18-19 km apart on opposite sides of the fault. Wagner (1978, p. 48 and Fig. 18) reports rather distinctive coarse conglomerate with Franciscan clasts in the Contra Costa Formation (formerly called Orinda) at two localities 24 km apart on opposite sides of the fault. According to Armstrong and others (1979), Prowell (1975) estimated total displacement at 16-17 km in the last 3.5 m.y., and possibly 65-72 km in the last 8 m.y. The figures for 8 m.y. seem too high, as rocks of that age are similar on both sides of the fault in the Pleasanton quadrangle. Kintzer and others (1981) matched a middle Miocene shoreline near Calaveras Reservoir with a similar one about 24 km away on the opposite side of the fault near Dublin.

Fold axes have also been used for estimating total strike slip along the Calaveras fault zone. This method assumes that the folds existed, at least incipiently, at the time strike slip commenced, and that displaced portions of folds can be matched with confidence. The folds probably grew concurrently with faulting, as both folding and faulting are Plio-Pleistocene. Crittenden (1951) estimated a 4.8 km displacement of the Tularcitos syncline by the Calaveras fault, but a small change in geologic mapping could make a large difference in the figure. (The syncline appears in the lower right-hand corner of Fig. 1). The Martin Canyon syncline on the southeast side of the Calaveras fault north of Dublin has sometimes been matched with the Welch Canyon syncline on the opposite side. If this is correct, the offset is 18 km.

The foregoing clues suggest to me that the total strike slip along the Calaveras zone, neglecting the extremities, has been on the order of 16-24 km, most likely about 20 km. If this has accumulated over 3.6 m.y., the geologic slip rate has been 0.56 cm/yr.

PRESENT BEHAVIOR OF THE FAULT ZONE

The southeastern part of the fault zone is a notably active component of the Pacific-North America plate boundary. It slips aseismically at an average rate of ca. 1.2 cm/yr (Evans and others, 1981), and shows an average geodetic movement of 1.5 cm/yr, as determined by laser geodimeters during the last 10 years (Prescott and others, 1981). If 5.7 cm/yr is the present relative plate motion (Minster and Jordan, 1978), the southeastern part of the Calaveras fault zone accommodates 26% of the total plate motion at this latitude.

Aseismic slip is detected both by continuous instrumental records (Evans and others, 1981) and by observation of damage to works of man. It is particularly evident in the town of Hollister, where streets, curbs, sidewalks, and houses are affected (Rogers and Nason, 1971). Creep is observed along the fault zone as far north as Welch Canyon between Calaveras Reservoir and Sunol, but none is detected with confidence north of Sunol. Along the actively creeping part of the zone, the creep rate is only slightly less than the geodetically measured movement rate across the zone. This would seem to imply that little elastic strain energy is accumulating; however, the surface creep may not extend to seismogenic depths. The part of the fault that is creeping is, in fact, very seismic.

North of Calaveras Reservoir, much of the seismicity, virtually all of the creep, and half the geodetic movement (0.75 cm/yr) transfer to the Hayward fault (Fig. 2), which exhibits these phenomena all the way to Berkeley and beyond. The transfer of motion from the Calaveras to the Hayward faut zone takes place at a left-hand stepover which, being in a right-hand system, is a locus of compression marked by thrusting (Aydin, 1982). In addition to unnamed thrusts, the Mission fault may provide some of the linkage between the two main fault zones. At deeper levels the picture may be somewhat different.

Seismic aspects of the Calaveras zone are summarized by Lee and others (1979) and Ellsworth and others (1982), and the maximum credible earthquake that might occur on the zone is estimated by Slemmons and Chung (1982).

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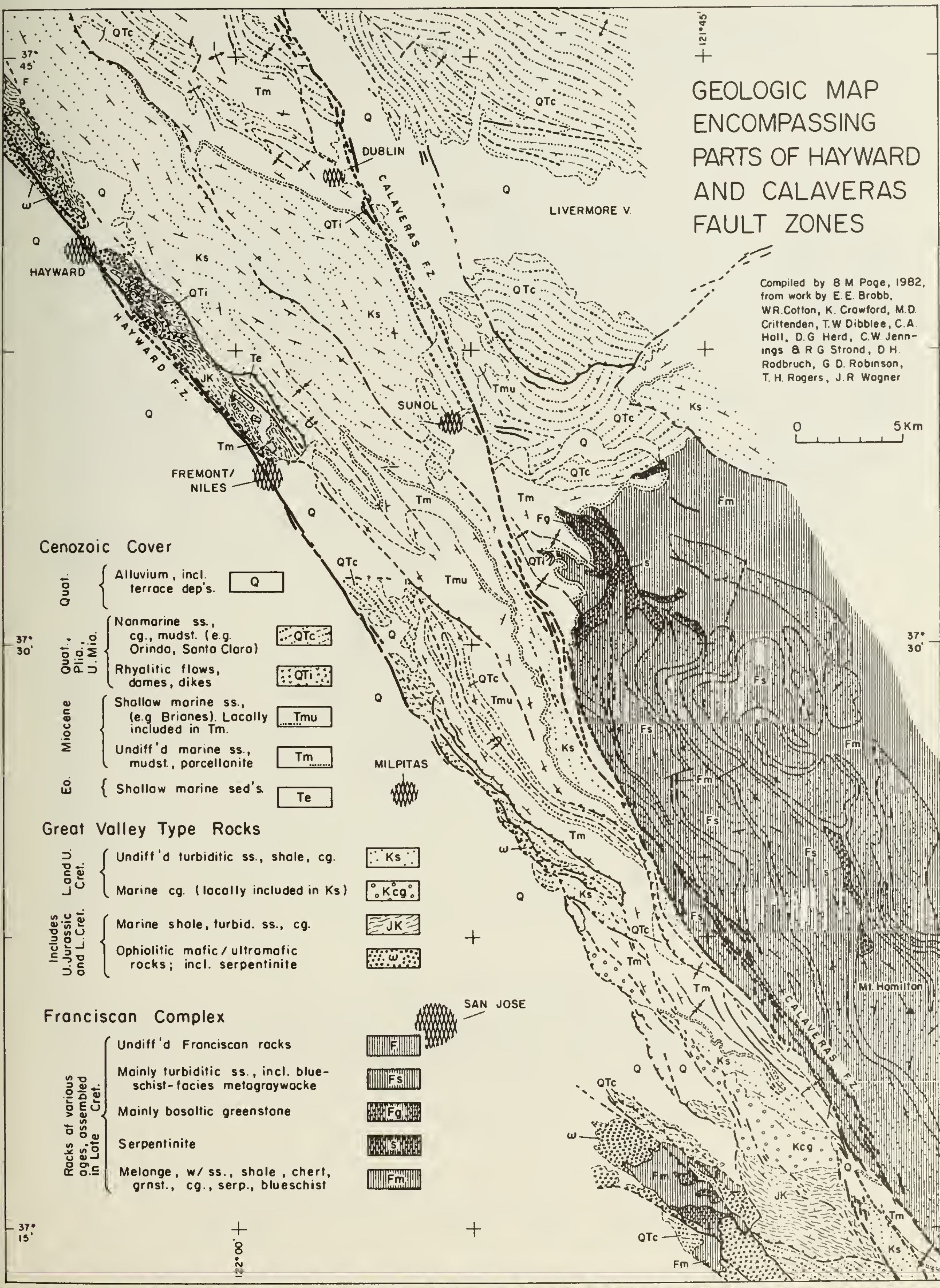

Figure 1. Geologic map showing parts of Hayward and Calaveras fault zones, California.

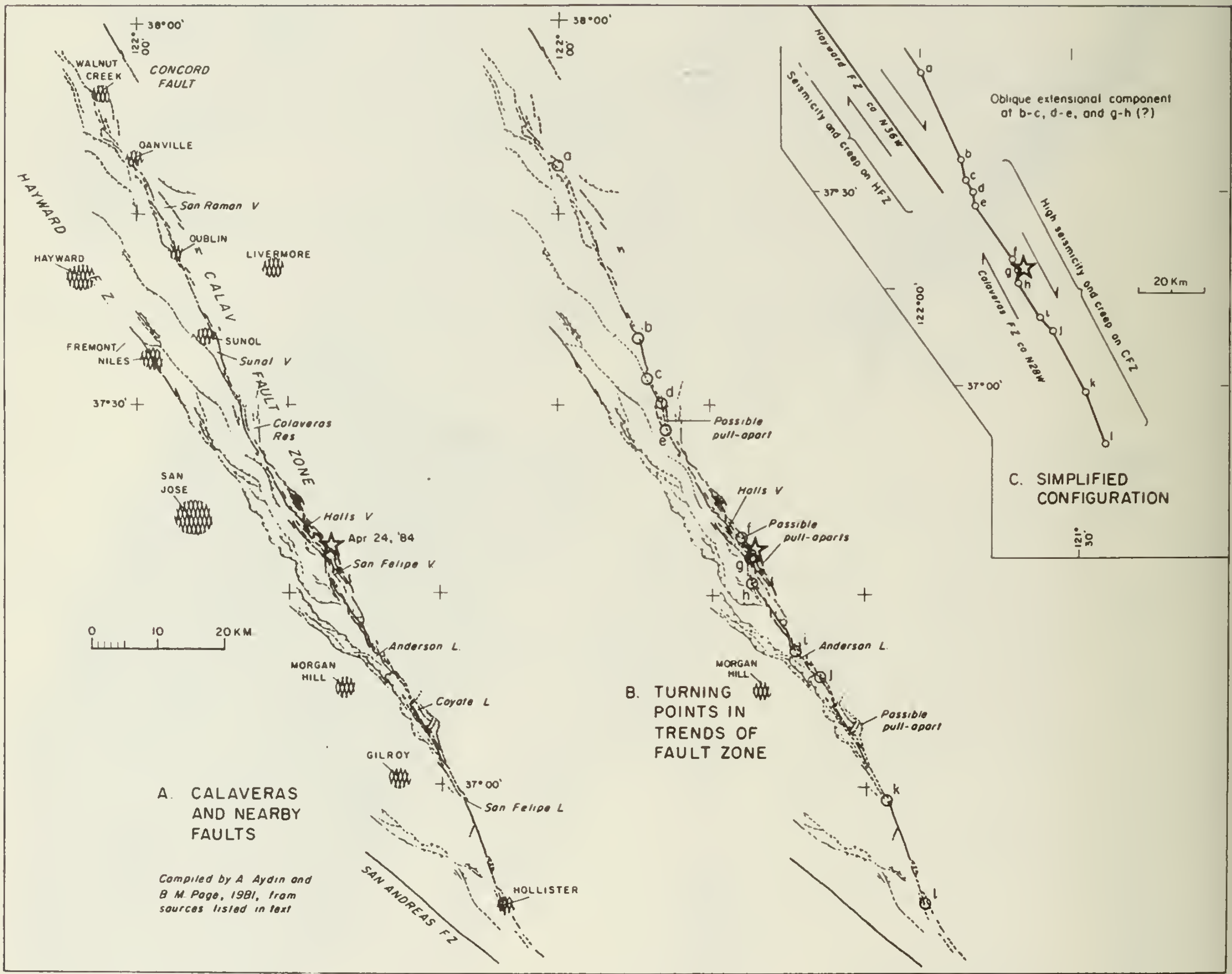

Figure 2. Configuration of Calaveras fault zone. In A and B, simple solid lines represent strike-slip faults, lines with sawteeth represent thrust or oblique-slip faults, and dashed lines represent probable (or poorly located) faults. In B, lettered circles represent turning points which are shown more explicitly in C.

SEISMIC VELOCITY STRUCTURE OF THE CRUST IN THE VICINITY OF THE MORGAN HILL, CALIFORNIA, EARTHQUAKE

by

Walter D. Mooney[1]

ABSTRACT

The crustal structure of west-central California in the area of the Morgan Hill earthquake is summarized based on recently completed seismic studies. The total crustal thickness is 26 km. The velocity structure of the lower crust is uncertain, but may include a pronounced seismic low velocity layer at a depth of about 20 km. Velocities in the middle crust (above 13 km) range from 5.8 to 6.2 km/s and are similar to those of the neighboring Diablo Range. The upper crustal structure of west-central California is complex, and includes rocks of the Franciscan melange, the Great Valley sequence, Tertiary sedimentary rocks, and Quaternary unconsolidated sediments. Seismic velocities in the shallow crust range widely, from 2.2 km/s to 6.0 km/s. A vertical seismic low-velocity zone has been identified at both the Calaveras and Sargent faults, but not at the San Andreas fault at the latitude of Watsonville. By combining all of the available infomation, a new average one-dimensional velocity structure for the epicental area of the Morgan Hill earthquake is proposed.

Introduction

Seismological studies of the main shock and aftershocks of the Morgan Hill earthquake of April 24, 1984, require a knowledge of the velocity structure in the epicentral region. This knowledge may be derived in part from the seismic refraction studies which have been conducted over the past two decades in this area of west-central California. These studies include long range (> 150 km) profiles within the Diablo and Gabilan Ranges, and shorter (< 50 km), profiles across the southern Santa Cruz Mountains and along the Calaveras fault. Together the available data define the essential features of the crustal structure, although significant gaps remain in our knowledge, and important aspects of the structure are open to alternative interpretations. The purpose of this paper is to review briefly the present state of knowledge of the crustal structure of west-central California, with particular emphasis on the epicentral region of the Morgan Hill earthquake. No new data are presented.

GEOLOGICAL SETTING

The Morgan Hill earthquake occurred on the Calaveras fault at a latitude of 37° 19' N, placing it about at the middle of this 120 km long fault. The Calaveras fault, part of the San Andreas fault system, is one of the most seismically active faults in central California. It and its southern continuation, the Paicines fault, are part of a system of right-lateral fault zones

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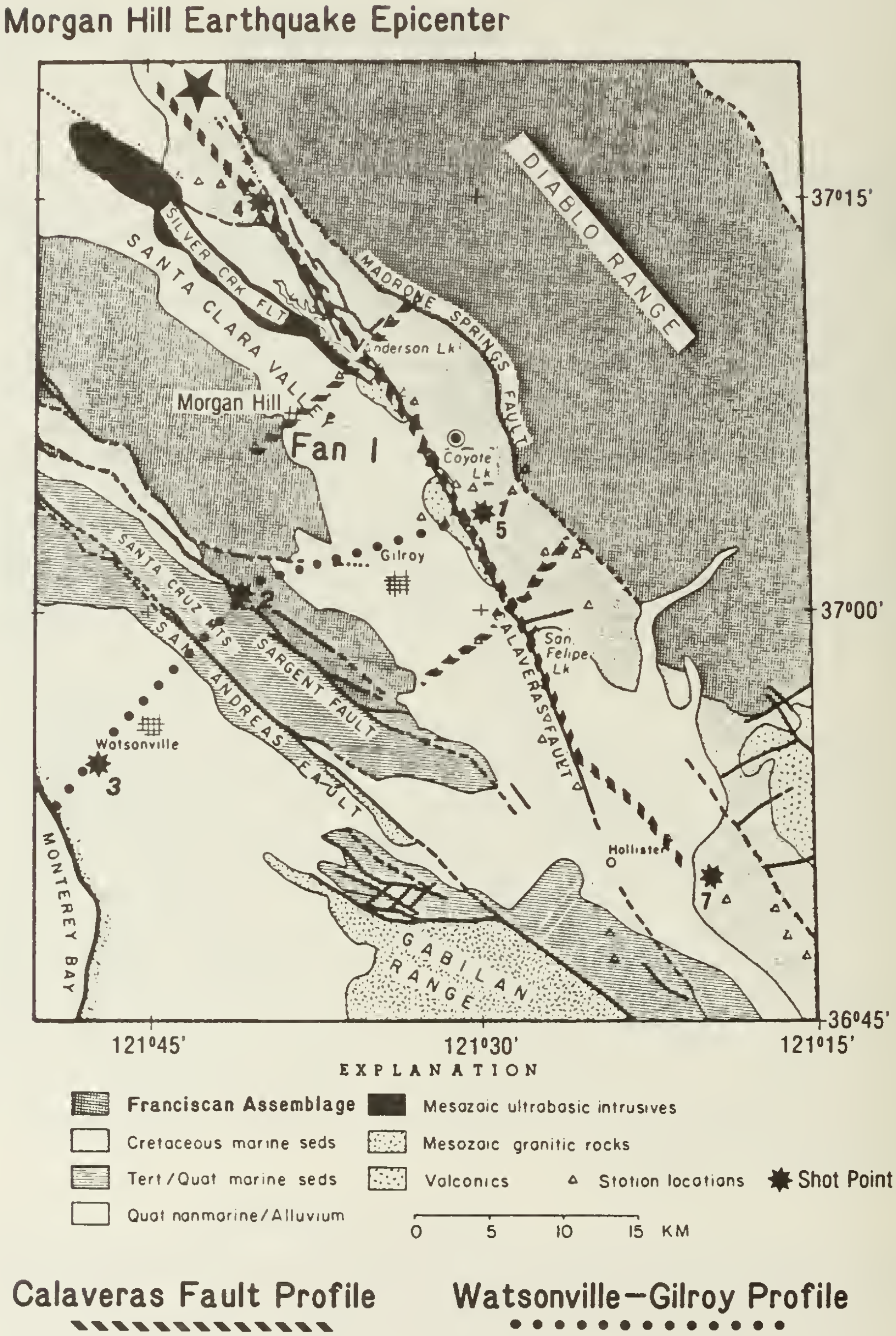

Figure 1. Location map of seismic refraction profiles in the vicinity of the Morgan Hill earthquake.

that branch northeastward from the San Andreas fault south of Hollister (Fig. 1). The Calaveras fault is considered active from Danville on the north to Hollister on the south. Page (1982b) estimates that 16 to 24 km of right-lateral slip has occurred on the fault in the last 3.6 my. The tectonic movement in the San Francisco Bay region is complex and has been discussed by Herd (1979) and Page (1982a). It involves right-lateral strike-slip motion along the San Andreas, Calaveras, and Hayward faults, and thrusting along the Foothills, Silver Creek, and Ben Lomond faults. Page (1982b) presents a modern review of the Calaveras fault zone and Bakun (1980) summarizes the seismic activity on its southern portion for a ten year period beginning in 1969.

In the epicentral area of the Morgan Hill earthquake (Fig. 1), the Calaveras fault zone borders the west side of the Diablo Range. The fault runs within low foothills on the east side of the Santa Clara Valley. The fault zone is a northwest-trending trench in which Coyote Lake and a portion of Anderson Lake are impounded. Eastward-dipping Great Valley sequence sandstones, shales, and conglomerates of Cretaceous age east of the Calaveras fault zone are juxtaposed against small bodies of serpentine, Jurassic-Cretaceous Franciscan assemblage shale, Tertiary volcanics, and Pliocene and Pleistocene sedimentary rocks (Bailey and others, 1964; 1970) (Fig. 1). North of Hollister the Calaveras fault crosses the southern end of the Santa Clara Valley, offsetting both late Pleistocene and Holocene alluvium. The fault zone is vertical to nearly vertical in practically all exposures.

CRUSTAL THICKNESS

We begin our discussion of the velocity structure with an examination of the total crustal thickness and upper mantle velocity. We then move through the crust, proceeding from the lower crust to the surface.

A recent study of earthquake traveltimes by Oppenheimer and Eaton (1984) provides by far the most complete contour map of the crustal thickness in central California. Their results indicate a crustal thickness of 26 km in the Morgan Hill area, with increasing crustal thickness to the east-northeast. They estimate the dip on the Moho to be 5.3° in the direction 66° east of north, with a mantle velocity of 8.0 km/s. The crustal thicknesses reported by these authors are in agreement with those derived from seismic refraction data by Walter and Mooney (1982) for the central Diablo and Gabilan Ranges. Although it has been suggested that there is an abrupt change in crustal thickness across the Calaveras fault, neither the refraction profiles nor traveltime studies have resolved it to date.

SEISMIC VELOCITIES IN THE LOWER CRUST

Considerable uncertainty exists concerning the seismic velocity structure of the lower crust in central California. This uncertainty arises from the inadequacies of all of the available data sources at this particular depth ($\sim$ 14 to 26 km). Unless very detailed data are collected, all seismic techniques can (and generally will) be interpreted in terms of a simple

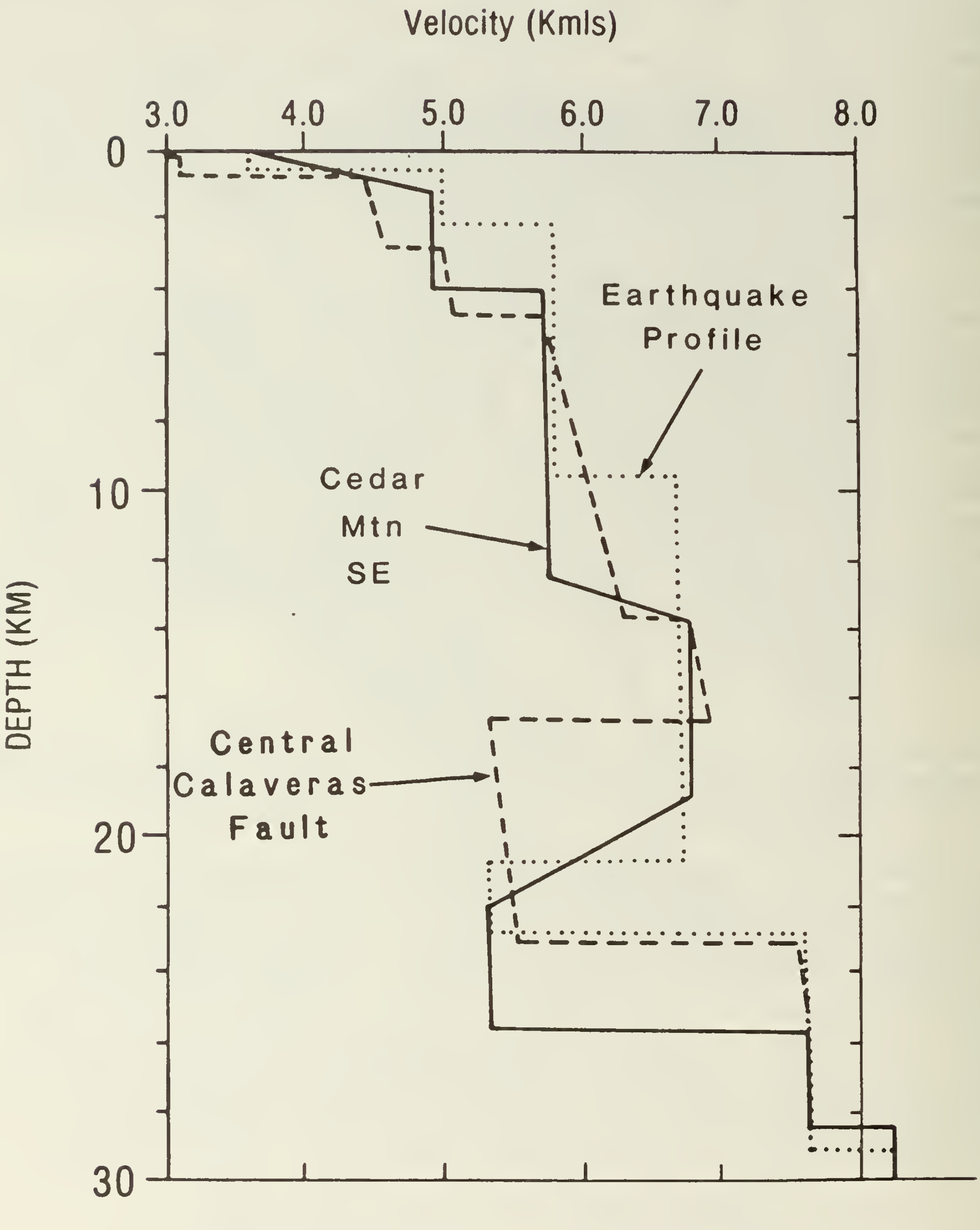

Figure 2. Velocity-depth profiles for the Diablo Range based on explosion and earthquake refraction data. The earthquake profile and Cedar Mtn SE profile are from Blümling and Prodehl (1983) and the Calaveras fault profile is from Blümling and others (1984).

homogeneous lower crustal velocity structure.

Walter and Mooney (1982) in their preferred model describe the velocity of the lower crustal structure of the Diablo Range in terms of a single 14 km thick layer with a velocity of 6.7 km/s at its top and 7.1 km/s at the crust-mantle boundary. A more complex model is suggested by Blümling and Prodehl (1983) and Blümling and others (1984) who have interpreted a pronounced seismic low velocity zone (LVZ) in the lower crust (Fig. 2) in central California. In their interpretation, the seismic velocity decreases from 6.8 km/s to about 5.3 km/s within the LVZ, at a depth of about 16 to 22 km. The detailed velocity structure of the LVZ is uncertain.

If their model is correct, it has substantial importance for geologic models of the evolution of the Coast Ranges of California. Whereas the velocity model of Walter and Mooney (1982) suggests that the lower crust of the Diablo Range consists of a 12-14 km thick layer of high velocity and high density (mafic) crust, the alternative model would replace this with a thin high velocity layer (with a thickness about equal to normal oceanic crust) overlying a layer of low velocity material. The interpretation of the composition and origin of this low velocity material (trench sediments (?), continental rocks (?)) then becomes an important geologic problem.

VELOCITY STRUCTURE OF THE UPPER CRUST BELOW 5 KM DEPTH

We here restrict the discussion to the seismic velocity structure in the epicentral area in the depth range 5 to 13 km. This depth was chosen to correspond to the depth below which detailed velocity models are available based on the interpretation of short-range seismic refraction profiles. This depth also corresponds to the depth below near-surface effects, such as weathering and open fractures.

Seismic refraction measurements (Walter and Mooney, 1982; Blümling and Prodehl, 1983; Blümling and others, 1984) indicate that the velocity at depths of 5 to 13 km is 5.9 ± 0.3 km/s. These interpretations model the structure either as one or more homogeneous layers, or as a single layer with a positive vertical velocity gradient. All interpretations indicate higher velocity (> 6.5 km/s) rocks below 13 km. These results are consistent with velocity estimates provided by the inversion of earthquake traveltimes (Reasenberg and Ellsworth, 1982; Thurber, 1983). Walter and Mooney (1982) discuss the geologic composition of the upper crust in this area of the Coast Ranges and conclude that it consists of rocks of the Franciscan Assemblage to a depth of about 13 km.

VELOCITY STRUCTURE OF THE UPPER CRUST ABOVE 5 KM DEPTH

The shallow velocity structure has not been examined with seismic refraction measurements in the immediate epicentral area of the Morgan Hill earthquake. However, two detailed profiles recorded to the south give a good indication of the regional near-surface structure and of the amount of lateral velocity variation.

1) Watsonville-Santa Clara Valley Line

In 1981, the U.S.G.S. recorded a seismic-refraction profile across the southern Santa Cruz Mountains, 50 km south of the epicentral area of the Morgan Hill earthquake. This 40-km-long profile extended northeastward from near Watsonville, California, to Coyote Lake, thereby crossing the San Andreas, Sargent, and Calaveras faults. This region is characterized by a complex upper crust. The interpretation of this profile (Mooney and Colburn, 1984) shows several important features. The composite interpretation of the crustal structure is shown with a vertical exaggeration of 2:1 in figure 3. We discuss the major features of the structure in some detail because it is the best available cross- structure seismic refraction profile in the area of the Morgan Hill earthquake.

At the west end of the profile, the alluvial fill of the Watsonville Valley amounts to 800-900 m. These are underlain by a layer with a velocity of 5.45 km/s at its top. Mooney and Colburn (1984) interpret this layer to be the top of a granitic layer which is the northwest continuation of the Gabilan Range. East of the San Andreas fault, the Tertiary sediments of the western Santa Cruz Mountains are about 2.5 km thick and are characterized by a seismic velocity of 3.34 km/sec. This low velocity indicates that the sediments are not highly metamorphosed. East of the Sargent fault, the near-surface rocks of the Franciscan assemblage of the eastern Santa Cruz Mountains have a seismic velocity of 4.5 km/sec, essentially the same as that measured at the near-surface in the Franciscan assemblage of the central Diablo Range (Walter and Mooney, 1982). At the easternmost flank of the Santa Cruz Mountains (at its boundary with the Santa Clara Valley) a region of low seismic velocity (about 4.0 km/sec) extends to several km depth. Based on the surficial geology we interpret this area to consist of sheared serpentine which migrated along steeply dipping faults within the Franciscan assemblage.

The strong ground motion experienced in communities located within the Santa Clara Valley makes a knowledge of the shallow velocity structure there important. The alluvial fill of the Santa Clara Valley thickens from west to east, reaching a maximum of 1.0 km at the latitude of Gilroy, somewhat less than the maximum fill of 1.5 km determined within the valley from the profile 6 km further south (Mooney and Luetgert, 1982). East of the Santa Clara Valley, on the west flank of the Diablo Range, rocks of the Great Valley sequence are exposed. In the upper 2 km, these rocks show apparent velocities of 3.0, 3.8 and 4.5 km/sec. True velocities were not determined on this profile but these velocities are consistent with the results of Blümling and others (1984) who analyzed a reversed seismic refraction profile which crosses this profile (discussed below).

If we define seismic basement as that horizon with a seismic velocity of 5.0 km/sec or greater, several prominent structures can be seen on this horizon. A buried fault occurs beneath the Watsonville Valley, with a vertical displacement (down on the east) of about 1.5 km. Following earlier geologic inference (Jennings, 1977) we suggest that this fault connects the Zayante fault of the west-central Santa Cruz Mountains with

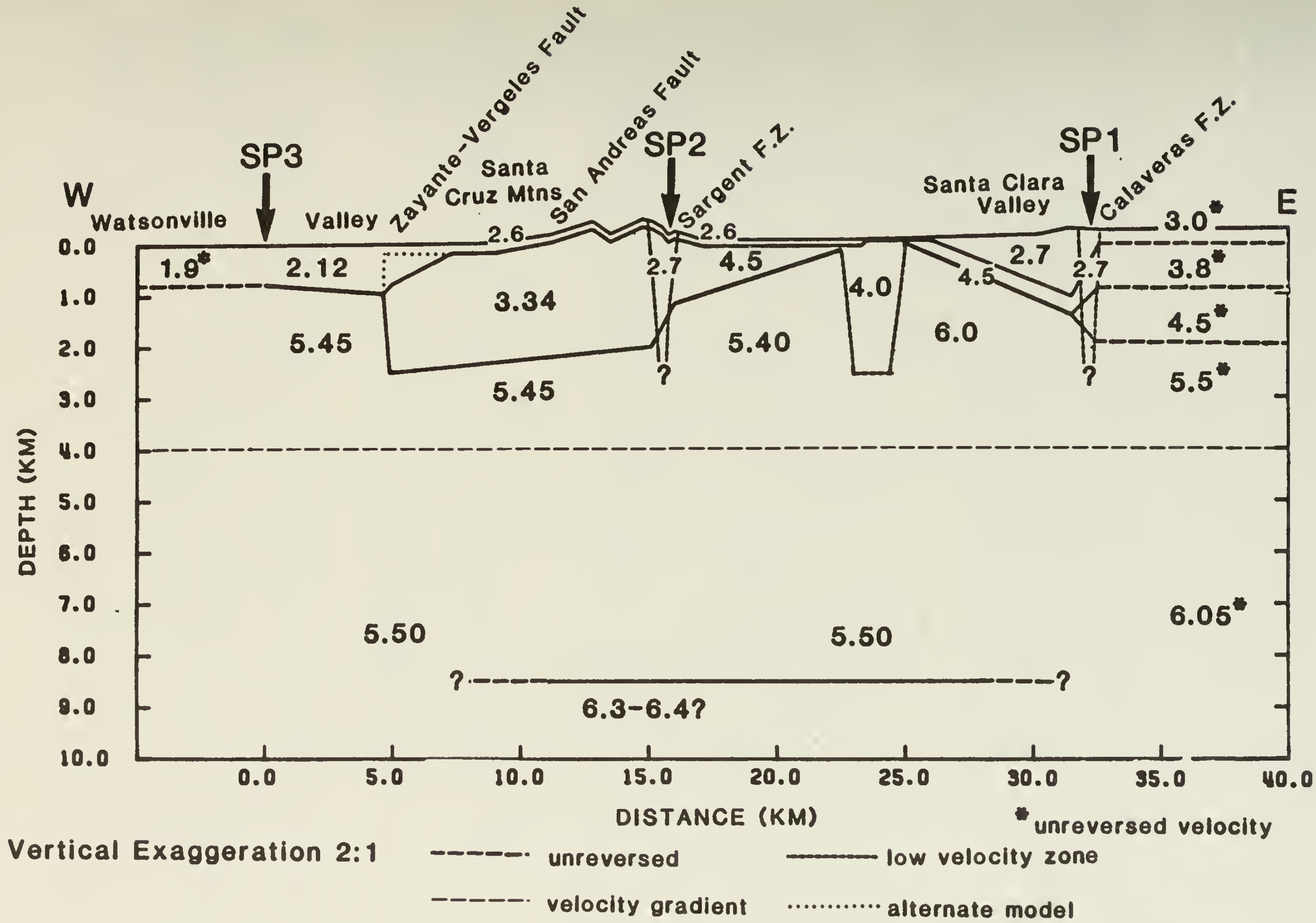

Figure 3. Velocity structure of the upper crust from Watsonville to east of the Calaveras fault. Shot point locations in figure 1. Velocities in km/s. Horizontal dashed line indicates a change in vertical velocity gradient. From Mooney and Colburn (1984).

the Vergeles fault of the Gabilan Range. In contrast to the large vertical offset on the Zayante-Vergeles fault, we observe no basement structural change across the San Andreas fault. The Sargent fault is marked by a 0.7 km rise (up to the east) on basement. In the area of the eastern Santa Cruz mountains and Santa Clara Valley the basement surface forms a broad anticlinal surface with a relief of 1.3 km. The zone of 4.0 km/sec seismic velocity occurs at the center of this anticline. The depth to seismic basement reaches 2 km east of the Calaveras fault.

The seismic velocity of basement may be expected to vary in the region of the Morgan Hill earthquake based on the results of the profile from Watsonville to Gilroy. For much of the profile the velocity is 5.4-5.5 km/sec, but it is 6.0 km/sec beneath the Santa Clara Valley. A higher seismic velocity for the basement rocks of the valley, which has also been reported by Mooney and Luetgert (1982), suggests a distinct geologic composition for these rocks. Based on the geology of the south-eastern Santa Cruz Mountains, previous seismic refraction measurements in the Coast Ranges (Stewart, 1968; Walter and Mooney, 1982; Blümling and Prodehl, 1983) and laboratory studies of Franciscan rocks (Stewart and Peselnick, 1977; 1978), we interpret the 6.0 km/sec rocks to consist mainly of meta-volcanic rocks assocated with the Franciscan assemblage. The remaining basement rocks, with seismic velocity 5.4-5.5 km/sec may consist of one of at least two rock types. At the shallow depths of the present measurements (1-3 km) both Franciscan assemblage metasediments and granitic rocks have seismic velocities in this range. Thus we can not define on the basis of seismic velocity alone where the basement rock type changes from the Franciscan assemblage of the eastern Santa Cruz Mountains to the granitic basement of the Watsonville Valley. The structure of the basement surface shows the largest changes at the Sargent and Zayante-Vergeles faults, rather than the San Andreas fault (figure 3), which suggests that the basement change occurs at one of the former faults.

The seismic-refraction profile crosses four major faults, three of which have major structural features. The vertical offsets at the Zayante-Vergeles and Sargent faults have already been noted; the Calaveras fault also appears to correlate with a basement offset (down on the east) of about 0.5 km. The Calaveras fault also is marked by a change in basement velocity from 6.0 to 5.5 km/sec.

Based on travel time delays, two faults, the Sargent and Calaveras, are interpreted to be characterized by seismic low velocity zones (LVZ's). The San Andreas fault does not appear to have a low velocity zone within it at this latitude, although a LVZ is present further south in Bear Valley, California (Feng and McEvilly, 1983). A LVZ at the Calaveras fault is well documented (Mayer-Rosa, 1973; Mooney and Luetgert, 1982; Blümling and others, 1984), but this is the first report of a LVZ at the Sargent fault. The depth extent of the LVZ's is not well determined by the present seismic data, but our raytrace calculations indicate that the LVZ extends into the basement rocks at a depth of 2 km and more.

Based on the evidece cited above, there appears to be a correlation of vertical LVZ's with seismically active faults, and no LVZ's with "locked" portions of the fault. This suggests that the material within the LVZ is produced by the gradual but continuous slip on the seismically active faults.

2) The Calaveras Fault Profile

Following the M5.7 earthquake of August 6, 1979 in the Coyote Lake area of the Calaveras fault (Fig. 1), the U.S.G.S. conducted a seismic refraction profile along and across the fault to obtain detailed P-wave velocity information within and near the fault zone. The profile consisted of a 70 km long main profile with average station spacing of 1-2 km, and two fan profiles perpendicular to the main line near the towns of Morgan Hill and Gilroy. The previously discussed profile from Watsonville to the Santa Clara Valley crosses the valley about 3 km north of the fan profile near Gilroy.

The seismic velocity structure determined along the fault is summarized in the model of figure 4. The structure was determined with greatest detail in the upper 5 km, and is modelled with planar layers (with vertical velocity gradients) below that depth. The near-surface layers (poorly consolidated sediments) have velocities of 2.75-3.2 km/s. These are thickest in the Hollister trough and in a basin near SP4 at the northern end of the profile. The next deeper layer has a velocity of 4.2-4.7 km/s and is of variable thickness. Based on surface exposures, we interpret this layer to consist mainly of the rocks of the Great Valley sequence. In the center of the profile, beneath SP 5, a 2-km thick layer occurs which is characterized by a velocity of 5.1 km/s. This layer extends for about 25 km along the fault, and appears to be an inclusion within the surrounding structure. Below 5 km the structure is essentially the same as that reported by Blümling and Prodehl (1983) for the Diablo Range. Velocities typical of Franciscan melange (5.7-6.3 km/s) occur to a depth of 14 km. The deeper structure has already been discussed.

The velocity structure within the Calaveras fault zone has been inferred from the fan profiles. Figure 5 shows the data for fan 1, the profile in the vicinity of the city of Morgan Hill. It is clear from these fan profiles that low velocities occur along the fault. The data from SP 4 show a very broad zone of traveltime delay due to the sedimentary basin located at that shot point, while the other two fans show a very pronounced delay (0.3-0.4 s with respect to adjacent seismograms) just at the fault trace. These data are interpreted as indicating a 1-2 km wide, vertical low velocity zone along the fault. Such a feature was reported by Mayer-Rosa (1973) based on earthquake traveltime data, and by Mooney and Luetgert (1982) based on seismic refraction data.

Proposed Seismic Velocity Structure in the Epicentral Area

Although no seismic refraction profiles have been recorded in the

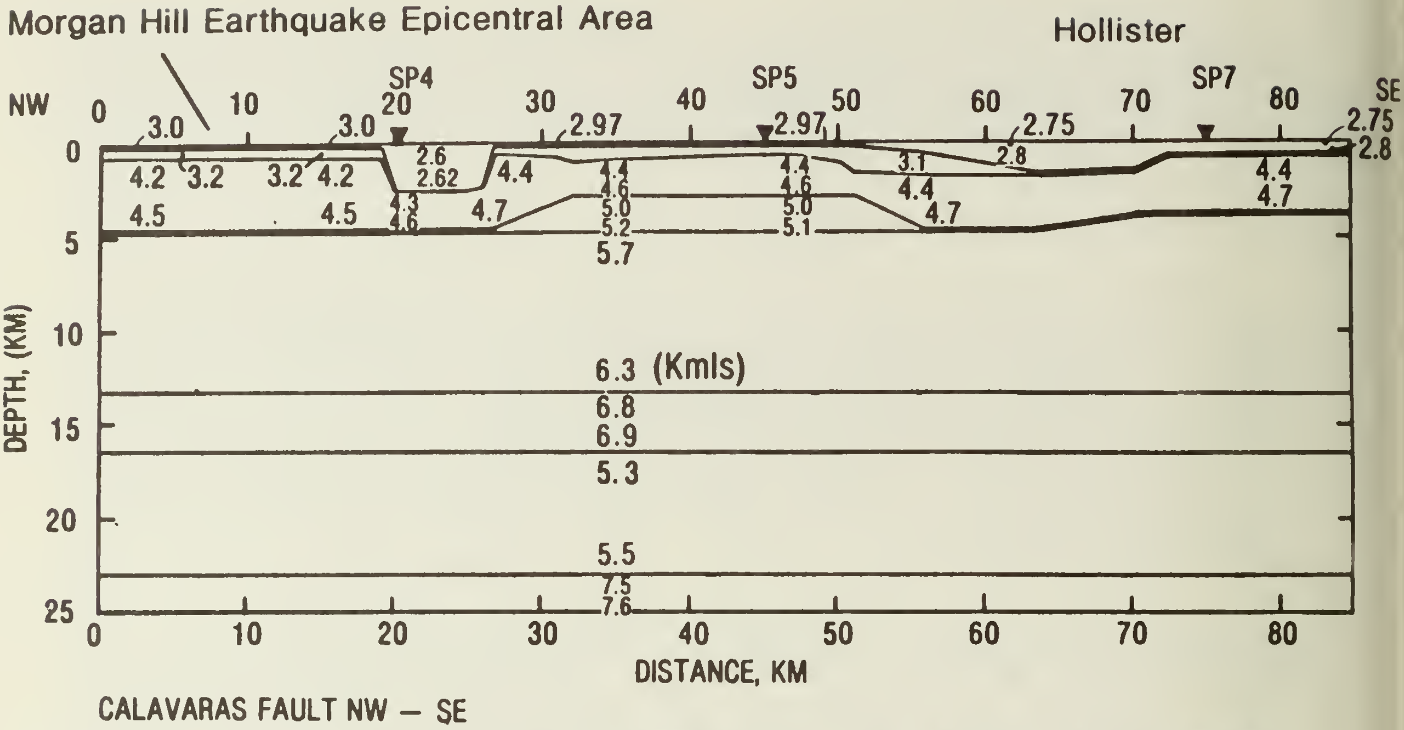

Figure 4. Velocity structure of the upper crust along the Calaveras fault. Shot point locations in figure 1. Probable geologic composition of each layer is discussed in the text. From Blümling et al., 1984.

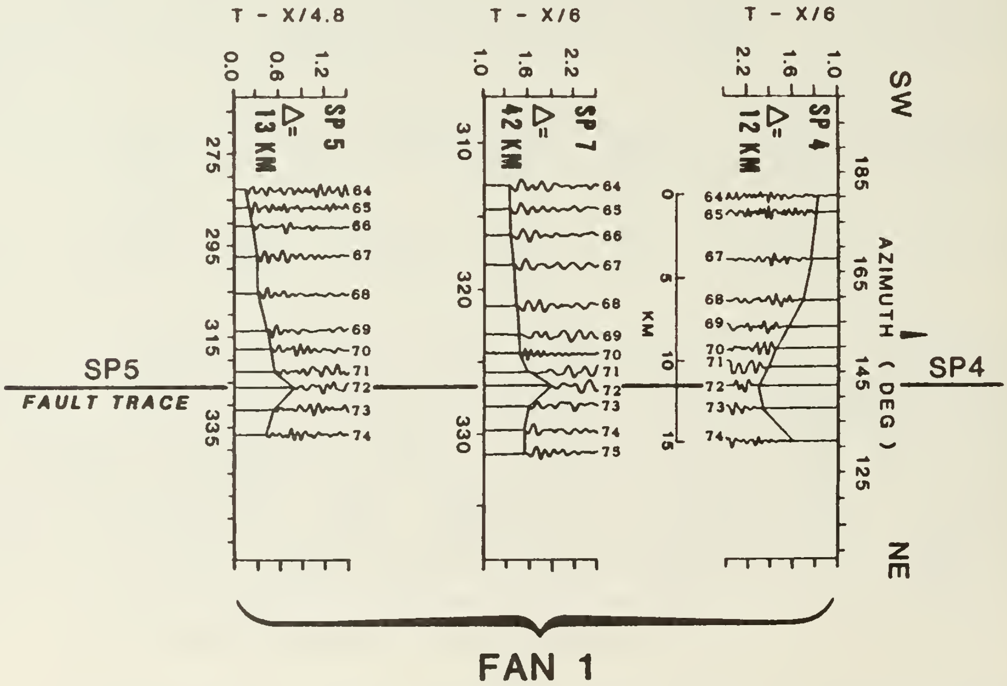

Figure 5. Fan profile across the Calaveras fault at the latitude of Morgan Hill. The three fans correspond to data from each of the three shot points (4, 7 and 5) in figures 7 and 4. There is a clear pronounced delay at the fault trace.

immediate epicentral area of the Morgan Hill earthquake, the available refraction data for west-central California allows us to estimate the velocity structure. We adopt Oppenheimer and Eaton's (1984) estimate of a crustal thickness of 26 km. The hypothesized lower crustal low velocity zone (Blümling and Prodehl, 1983; Blümling and others, 1984) is best constrained by the seismic data in the area of the epicentral area, so we include it in our velocity model. The middle and upper crust below 5 km almost certainly has a velocity structure similar to the neighboring Diablo Range.The near-surface velocity structure is known to be as complex as the local geology; we have used a two-layer near surface structure based on the Calaveras fault model. The proposed model is shown in figure 6 and is summarized in Table 1.

Table 1.

Proposed velocity-depth function for the epicentral area of the Morgan Hill earthquake (c.f., Fig. 6). All "layers" have positive vertical velocity gradients, and repeated depths indicate velocity discontinuities.

DEPTH (KM)	VELOCITY (KM/s)
0.0	3.0
0.7	3.2
0.7	4.2
4.5	4.5
4.5	5.7
14.0	6.2
14.0	6.8
16.5	6.9
16.5	5.3(?)
23.0	5.5(?)
23.0	7.5
26.0	7.6
26.0	8.0
40.0	8.1

ACKNOWLEDGEMENTS

The information summarized here was determined from seismic field data collected through the efforts of a large number of people. We thank the following USGS field staff for their diligent efforts: E. E. Criley, R. P. Meyer, Jr., V. D. Sutton, L. R. Hoffman, J. N. Roloff, S. S. Gallanthine, G. A. Molina, J. Van Schaak, R. H. Colburn, J. M. Murphy, T. Reed, and W. M. Kohler. Discussions with P. Blümling, W. H. K. Lee, C. Prodehl and A. W. Walter have been valuable. Comments on the manuscript by M. C. Andrews, J. P. Eaton, J. H. Luetgert, and A. W. Walter are appreciated.

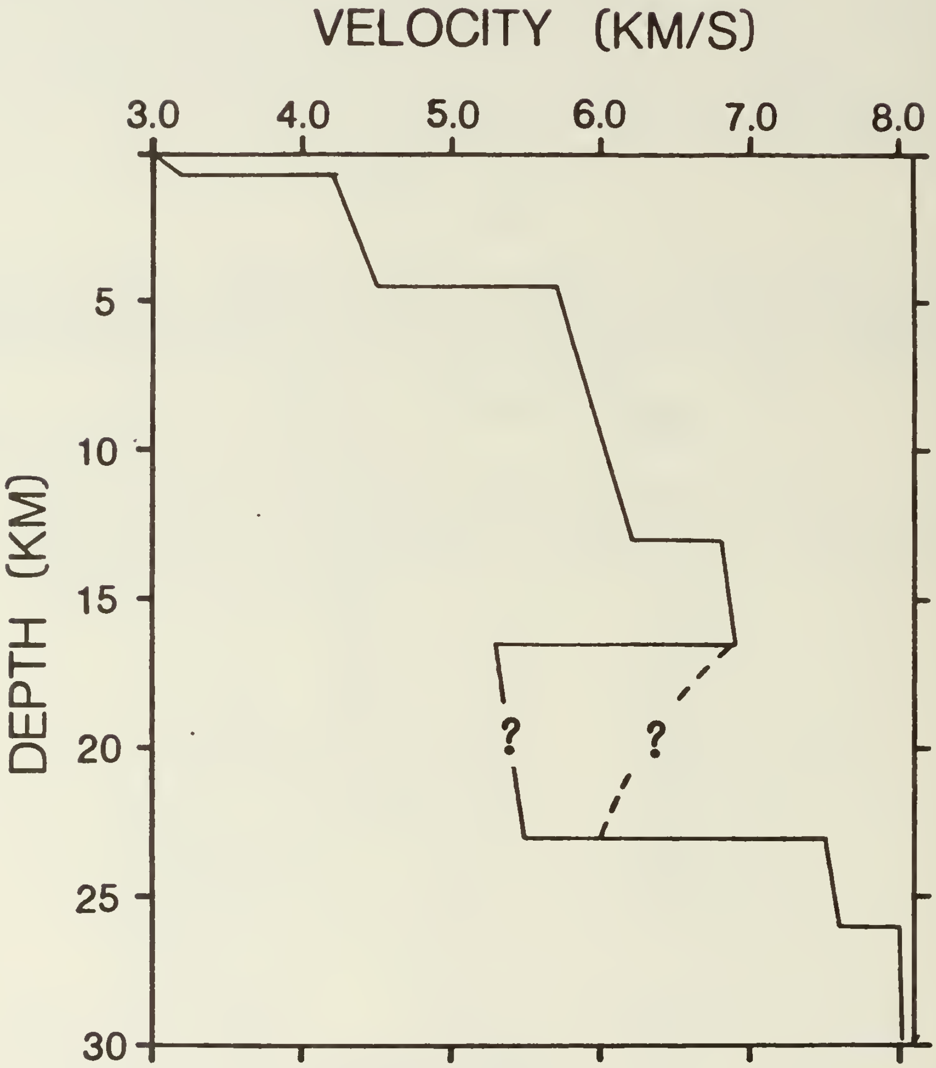

Figure 6. Proposed velocity-depth function for the epicentral area of the Morgan Hill earthquake based on the data described in the text. Note that this one dimensional model is an average for an area of pronounced lateral velocity variations, and that a vertical low velocity zone along the Calaveras fault (c.f., Fig. 3) is not shown. The velocity and depths are given in Table 1.

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PRESEISMIC, COSEISMIC AND POSTSEISMIC DEFORMATION ASSOCIATED WITH THE 1984 MORGAN HILL, CALIFORNIA, EARTHQUAKE

by

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ABSTRACT

The Morgan Hill earthquake of 24 April 1984 occurred in the middle of a network of geodetic lines. Lines within 5 km of the epicenter were measured 2 weeks, 8 days and 1 day prior to the earthquake. None of the preearthquake measurements is unusual. At the 95% confidence level, the preseismic observations exclude a precursory slip event of greater than 80 to 140 mm. A small aperture geodetic network located 5 km northwest of the epicenter was observed 2 weeks prior to the event. It indicated no detectable preseismic surface slip had occurred. The geodetic data suggest that the event involved about 425 mm of slip on a surface defined by the aftershocks producing a moment of 1.9×10^{25} dyne-cm. Slip on the fault near the surface in Hall's Valley during the event was at most about 8 mm and may have been zero. Additional slip at depth occurred during the months following the earthquake. As of August 1984, this postseismic slip had amounted to 335 mm.

INTRODUCTION

A dense network of geodetic lines, some measured monthly, surrounded the epicenter and aftershock zone of the Morgan Hill earthquake. The epicenter and NW end of the aftershock zone was located 5 km from Mt. Hamilton, one station of a large aperture geodetic network (average line lengths of greater than 20 km), and they were less than 5 km from Grant Ranch, a small aperture geodetic network (typical line lengths of about 5 km). All of these lines had been measured many times prior to the earthquake. The line to Mt. Hamilton is part of an experiment specifically designed to search for precursors prior to earthquakes. It has been measured monthly for several years. This line was measured 8 days prior to the earthquake and again on the day preceding the earthquake. The Grant Ranch network had been measured just two weeks prior to the event. Consequently this earthquake provided a unique opportunity to look for evidence of preseismic slip or other geodetic anomalies. In addition all of these lines have been remeasured since the earthquake, and place constraints on the coseismic and postseismic slip. All distances were measured

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either with a geodolite using techniques described by Savage and Prescott (1973) or with an HP 3800 series instrument using techniques described by Lisowski and Prescott (1980).

PRESEISMIC DATA

The earthquake epicenter is located about 20 km east of San Jose, California (Figure 1) in Hall's Valley at the foot of Mt. Hamilton. Mt. Hamilton is one of four stations in a network that the U.S. Geological Survey has measured nearly every month since September 1981. Prior to the earthquake none of the lines had shown any unusual variation in length. In particular, the observations made during the months, weeks, and days prior to the earthquake do not stand out at all. The most interesting line is the line from Loma Prieta to Mt. Hamilton. This line was measured 8 days before the earthquake and again on the day preceding the earthquake (Figure 2). These two measurements are within 3.4 and 1.5 mm long compared to an extrapolation of the previous measurements. Since the standard deviation of a single measurement of this line is 7 mm, it is clear that these measurements were not in any way anomalous. The Loma Prieta to Mt. Hamilton line crosses the Calaveras fault at an angle of 65°. Such a high angle is less than ideal for detecting strike slip movement on the Calaveras fault, but it does have the advantage of also being somewhat sensitive to motion normal to the fault. Thus, if a precursory episode of either right-lateral strike slip or of normal dilatation (dilantancy) occurred more than 24 hours prior to the earthquake, and if it was of sufficient magnitude, it would have been detected. The qualification, "of sufficient magnitude", is an important one. The question of how large a precursory slip event could have occurred without producing a detectable change in the line Loma Prieta to Mt. Hamilton is best answered in the context of the models for the coseismic slip, and will be covered in the discussion at the end.

The only other line with a long history of frequent observations, that has any bearing on this earthquake is the line Loma Prieta to Allison (Figure 1). This line has also been measured monthly since 1981, however, it was not measured in the week prior to the earthquake. Station Allison is located between the Calaveras and Hayward faults and is more distant from the epicenter of the Hall's Valley earthquake than Mt. Hamilton. No significant changes in the length of this line were observed prior to the earthquake.

The Grant Ranch network is a collection of short lines located in Hall's Valley (Figure 1). This network has been surveyed occasionally since 1977. There is some uncertainty about the location of the active trace of the fault in Hall's Valley. Dibblee's (1973) map indicates traces on both sides of station Barn (Figure 3). Herd (Harms et al., 1984) indicated a single trace passing northeast of station Barn. In the interests of brevity, only the data for the low angle fault crossing lines of the network are shown in Figure 3. Changes in the length of the lines Barn to Halls and Halls to Pueblo, suggest that some surface fault slip (creep) has been occurring on the northeastern side of the network. The line Barn to Yerba is more ambiguous, but may indicate that additional slip is occurring along the fault strand southwest of station Barn. Assuming rigid block motion the average slip rate across the network over the 7 years of observation has been 9.4 ± 0.4 mm/a, 6.5 mm northeast of Barn and 3.0 mm southwest of Barn. The last survey prior to the

earthquake was made 2 weeks before the event. There is no evidence of any unusual change in the lengths of these lines prior to the earthquake. The length of the lines and the location of the stations are such that the net is only affected by fault slip occurring at the surface, whereas the longer lines are also sensitive to slip at depth.

COSEISMIC DATA

Immediately after the earthquake, all of the lines in the area were reobserved. Some of the Grant Ranch lines were remeasured on the afternoon of the earthquake. The rest of the Grant Ranch network was measured on the 25th of May and a few lines were repeated on the 26th. The line Hamilton to Loma Prieta was observed on both the 25th and 26th. The line Hamilton to Llagas was observed on both the 26th and 27th. The remaining lines were each measured once after the earthquake (Figure 4). The observed changes are summarized in Table 1. For the line Hamilton to Loma Prieta the 'before' length is the last measurement prior to the earthquake. For lines measured earlier the 'before' length was calculated by extrapolating a least-square-linear-fit forward to 24 April 1984, the day of the Morgan Hill earthquake. The 'after' length is the mean of all the measurements made after the earthquake. There are significant changes in many of the lines in the area, but most of the changes are modest; the largest is 56 mm.

The observed changes in the lengths of these lines place constraints on the amount of slip that occurred during the main shock. In modeling these changes we assumed that the rupture plane of the mainshock was defined by the distribution of aftershocks. Aftershocks during the week following the event defined a surface extending southeast from the main shock hypocenter for about 25 km; the aftershocks were distributed between 4 and 10 km (Bakun et al., 1984). We modeled the earthquake as a uniform strike slip discontinuity on a rectangular, vertical surface embedded in an infinite elastic half space (Chinnery, 1961). Using a least-squares process, the amount of slip that best fit the observed coseismic line length changes was determined to be 425 $\pm$ 40 mm. Although the slip appears very well determined, it should be recognized that the error estimate is conditioned on the assumption that there is no uncertainty in the dislocation geometry. Altering the geometry produces changes much greater than might be suggested by the 40 mm uncertainty quoted above. In general the solution was insensitive to the length of the dislocation as long as the northwest end was fixed at the main shock hypocenter. Decreasing the depth, while maintaining a constant dislocation width, caused the estimated slip to decrease by about 140 mm per km of decrease in depth. The geodetic data are not adequate to constrain the geometry of the slip surface by themselves. In part this is due to an inherent difficulty in placing constraints on slip at depth from measurements made at the surface, and in part, the difficulty stems from the small size of the observed changes. The line length changes imply a geodetic moment of 1.9×10^{25} dyne-cm (assuming a rigidity of 3×10^{11} dynes/cm^2). For comparison the Coyote Lake earthquake of 1979, that occurred on the next section to the southeast had a geodetic moment of 1.6×10^{25} dyne-cm (King et al., 1981).

Coseismic changes in the Grant Ranch network were very small. There was no change in the Barn to Halls line, indicating that no slip occurred at the surface on the northeastern side of the network. The two lines crossing the

southwestern side at low angle changed slightly, -8 mm and +5 mm. These changes were in a direction consistent with right-lateral slip, but are only marginally above even a one sigma noise level. If coseismic slip occurred at the surface in Hall's Valley, it was at most about 8.5 mm, and occurred on the southwest side of station Barn. In contrast the slip during the 7 years preceding the earthquake appears to be concentrated on the northeast side of station Barn. The absence of coseismic slip at Grant Ranch is consistent with the observations that Grant Ranch is located slightly northwest of the epicenter of the main shock, that the rupture appears to have propagated to the southeast, and that no evidence of surface rupture has been detected anywhere along the aftershock zone.

POSTSEISMIC DATA

During the months after the earthquake, the lines Hamilton to Llagas and Hamilton to Loma Prieta were measured every few weeks (Figure 5). Very little further change was detected in the Hamilton to Loma Prieta line, but the Hamilton to Llagas line continued to shorten. Changes in the line Hamilton to Llagas imply that afterslip occurred at a rate of 12 mm/day for the first two weeks after the earthquake. As of August 1984, the implied afterslip rate is about 0.8 mm/day.

Ascertaining the location of the postseismic slip is subject to the same uncertainties that complicated constraining the coseismic slip with two additional complications. It is no longer valid to assume that the slip occurred on the portion of the fault plane defined by the aftershocks; and because the postseismic slip was smaller than the coseismic slip, it is that much more difficult to detect. Furthermore, we have not yet reobserved all of the lines that would be useful in constraining postseismic slip. However, the existing data suggest that the postseismic slip is probably shallower than the coseismic slip. If the postseismic slip occurred between 4 and 10 km depth like the coseismic slip, about 300 mm of postseismic slip would be required to produce the observed change in the Hamilton to Llagas line (Figure 5). 300 mm of slip would produce a 24 mm change in the line Hamilton to Loma Prieta, but there is only evidence of about 17 mm of decrease in the length of the Hamilton to Loma Prieta line. This fact suggests that the postseismic slip may be more shallow than the coseismic slip (and thus affected the more distant station Loma Prieta less). If the postseismic slip is more shallow than the coseismic slip, then less than 300 mm would be required to produce the observed change in the Hamilton to Llagas line.

Although the geodetic data suggest that the postseismic slip is shallower than the coseismic slip, there is no evidence to suggest that it has continued the rupture all the way to the surface. Observations of an alinement array in San Felipe Valley, 5 km southeast of the epicenter, had not indicated any postseismic slip as of 21 June 1984 (B. Brown, pers. comm.). Similarly the Grant Ranch network has shown no evidence of postseismic movement. In this respect the Morgan Hill earthquake differs significantly from the Coyote Lake earthquake of 1979. After Coyote Lake, postseismic slip extended all the way to the surface and amounted to nearly 100 mm, about 1/3 of the coseismic slip (Lisowski and King, unpub. ms.).

DISCUSSION

One question of interest is how large a precursory slip event could have occurred and where could it have occurred without producing a detectable line length anomally. Although the line Hamilton to Llagas is most ideally situated for detecting slip on the coseismic rupture surface, it had not been surveyed during the two months preceding the earthquake. Data for the line Hamilton to Loma Prieta gives much better temporal resolution at the expense of spatial resolution. From the calculated slip listed in the next to the last column of Table 1 one can calculate how much slip could have occurred prior to the event without causing a detectable change in the length of the line Hamilton to Loma Prieta. The dislocation model indicates that 425 mm of slip on the aftershock surface would produce a -31.3 mm change in the length of the line Hamilton to Loma Prieta (Table 1). The measurement made the day before the earthquake was 1.5 mm long compared to the extrapolation of the previous measurements. The average of the 2 measurements made during the week before the earthquake was 2.4 mm long compared to the extrapolation of the previous measurements.

The question of how much slip might have occurred prior to the earthquake can be phrased more precisely as follows: What is the probability that preseismic slip was less than some specified amount? The probability obviously depends on the level we choose. An expression for the probability is derived in the Appendix and the probability is plotted as a function of the level in Figure 6. It is apparent from Figure 6 that rather large amounts of slip could have occurred prior to the earthquake without producing a reliably detectable signal. For example, we can state with 95% confidence that, if a precursory slip event occurred more than a week before the earthquake, the magnitude had to be less than 80 mm. Similarly for precursory slip occurring between 1 week and 1 day before the earthquake, at the same 95% confidence level, the slip had to be less than 140 mm.

It is clear from Figure 6 that we can make no meaningful statements about the possibility of precursory slip unless that slip is a sizeable fraction, 20% to 30%, of the coseismic slip. Because the observations are so insensitive to small amounts of slip, it might be argued that these data are irrelevant. However, it should be recalled that much of the interest in the possibility of precursory slip stems from observations of possible precursory slip associated with the 1966 Parkfield earthquake. Allen and Smith (1966) reported that fresh cracks were observed in a road near Parkfield 11 days prior to the earthquake. Yerkes and Castle (1967) describe damage to an irrigation pipeline at an elbow where the pipe turns to cross the fault zone. 9 hours before the 1966 Parkfield earthquake the pipe ruptured and developed 600 mm (2 feet) of offset at the point of rupture. While it is far from clear that the pipe rupture was caused by precursory slip (the point of rupture was near but not at the point where the pipeline crosses the fault), it does indicate that the observations reported here may be of some value even though they only constrain the preseismic slip to less than 80-140 mm.

This discussion assumes that the precursory slip, if any, occurred on the same plane as the 24 April earthquake. Other scenarios are possible. Since the epicenter was located at the northwestern end of the aftershock zone, it is conceivable that precursory slip might occur along the section of the Calaveras fault located to the northwest of the aftershock zone (Figure 1).

Because Hamilton is located so close to the end of the aftershock zone, the Hamilton to Loma Prieta line would be nearly as sensitive to slip on this fault section as it is to slip on the aftershock zone. Thus an upper limit to the size of a possible undetected precursory slip event is similar. In fact precursory slip on the next section to the northwest is even less likely since another of the monitor lines, from Loma Prieta to Allison, would be expected to be sensitive to slip along that section. This line was measured one month before the earthquake. We conclude that if any buried preslip occurred it must of been of less than about 80 mm. Or it must have involved a portion of the fault surface smaller than the aftershock surface. To be detectable in amounts as small as 80 mm, the preslip would have to involve a substantial portion of the fault plane. Much greater amounts of slip could have occurred on smaller portions of the fault surface without being detected.

The small aperture network located in Hall's Valley places a further constraint on the possible occurrence of slip prior to this earthquake. The Grant Ranch network is located within 5 km of the epicenter and was measured 2 weeks before the event. No anomalous deformation was observed. This network is insenitive to slip at depth because of its small scale, but it is quite sensitive to surface slip. The observations tell us that no significant amount of accelerated creep preceded the earthquake; at least not NW the epicenter, not 2 weeks before the earthquake, and not exceeding about 20 mm.

As of August 1984 postseismic slip following the earthquake had amounted to 80% of the coseismic slip. Postseismic slip was continuing to occur at a slow rate. The afterslip differs from that occurring after the 1979 Coyote Lake earthquake. The Morgan Hill afterslip is larger in comparison to the coseismic slip. Although the Morgan Hill afterslip appears to be somewhat shallower than the coseismic slip, there is no evidence that it has propagated all the way to the surface as appeared to be the case after the Coyote Lake event.

APPENDIX

Let S_h = hypothesized precursory slip,
and S_a = actual precusory slip.

We want to calculate the probability $P\ (S_a < S_h)$.

Let o = observed change in line length,
σ = standard deviation in o,
and c (s) = calculated change in line length for a slip s.

Then because of the linearity in the dislocation model

$$c(s) = \frac{-31.3}{425}\,s$$

The statistic

$$t(s) = \frac{o-c(s)}{\sigma}$$

is normally distributed and the probability $P\ (S_a < S_h)$ is equivalent to the probability $P\ (\ t < t(S_h))$. For a given value of S_h the required probability

can be obtained from tables for the normal distribution. For a 1 day precursor, o = +1.5 mm and σ = 7 mm. For a 1 week precursor o = +2.4 mm and σ = 5 mm, from the average of the measurements one day and one week before the earthquake.

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Table 1. Change in line lengths at the time of the Hall's Valley Earthquake. For lines that were measured more than a month prior to the earthquake, the before length is calculated by extrapolating the earlier observations to the time of the earthquake.

Station Names		Before (M)	After (M)	Diff. (mm)	Model (mm)	Std. Dev. (mm)
Allison	Hamilton	26696.0857	.0995	13.8	19.6	6.1
Allison	Loma Prieta	43129.1733	.1896	16.3	-4.9	9.1
American	Hamilton	20649.1734	.1845	11.1	2.8	5.1
Gilroy	Llagas	17601.1574	.1476	-9.8	11.4	4.6
Hamilton	Llagas	23178.1347	.0788	-55.9	-58.5	5.5
Hamilton	Loma Prieta	31227.9758	.9501	-25.7	-31.3	6.9
Hamilton	Sheep	27435.0842	.0610	-23.2	-20.3	6.2
Hamilton	Mt. Stake	20897.4510	.4526	1.6	6.2	5.1
Hamilton	Mocho	16914.6944	.7146	20.2	16.0	4.5
Hamilton	Mt. Oso	30082.4161	.4422	26.1	18.1	6.7
Hamilton	Rose	20143.6586	.6847	26.1	22.0	5.0
Llagas	Loma Prieta	15940.5697	.5929	23.2	4.2	4.4
Llagas	Sheep	13539.0145	.0411	26.6	19.1	4.0

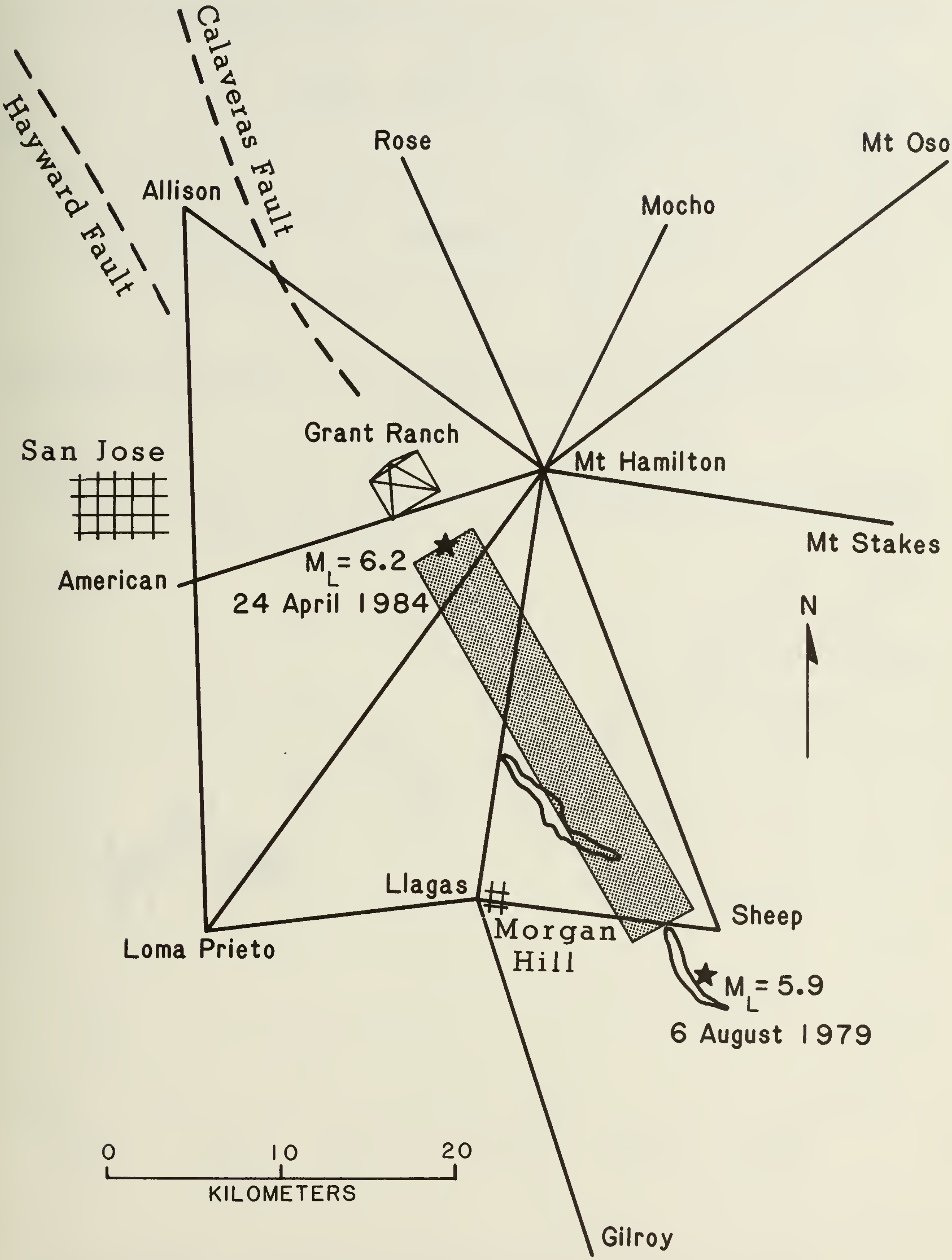

Figure 1. Map of the area covered by the geodetic network. Box contains aftershocks located during the first week following the earthquake (Cockerham, pers. comm.).

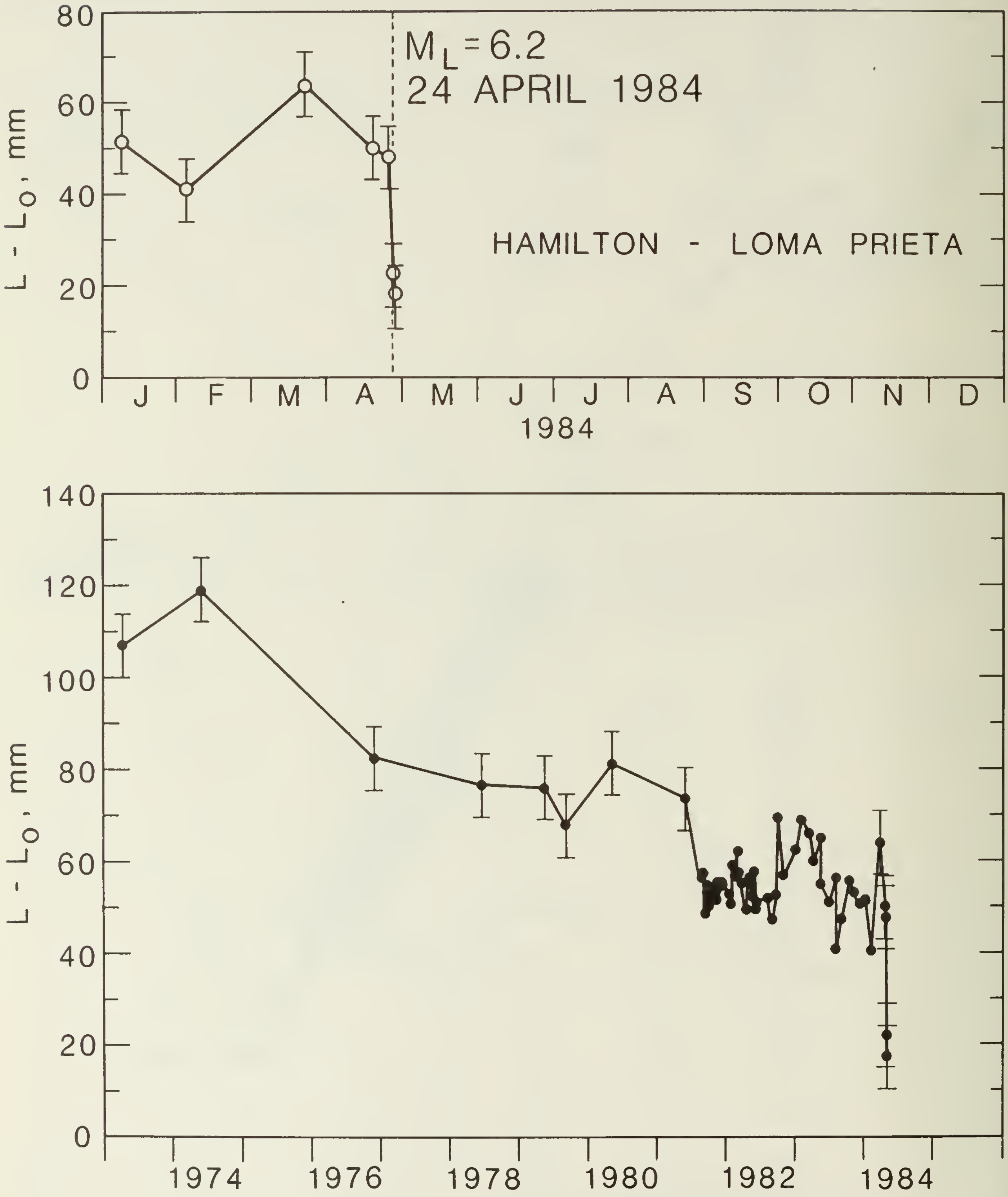

Figure 2. Plot of the length of the line Hamilton to Loma Prieta as a function of time. The last year's measurements are also shown on an expanded time scale. Error bars indicate plus and minus one standard deviation.

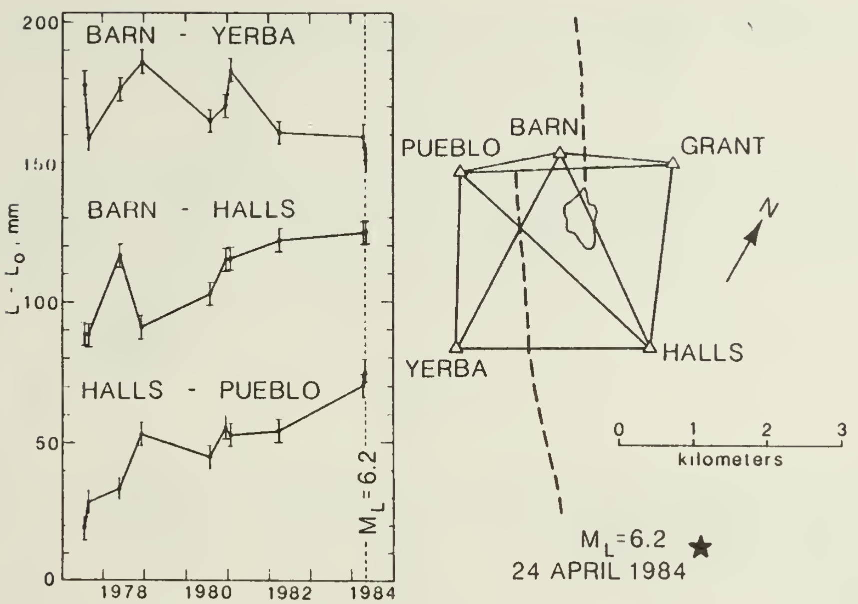

Figure 3. Plot of the length of low angle fault crossing lines in the Grant Ranch network. Error bars indicate plus and minus one standard deviation.

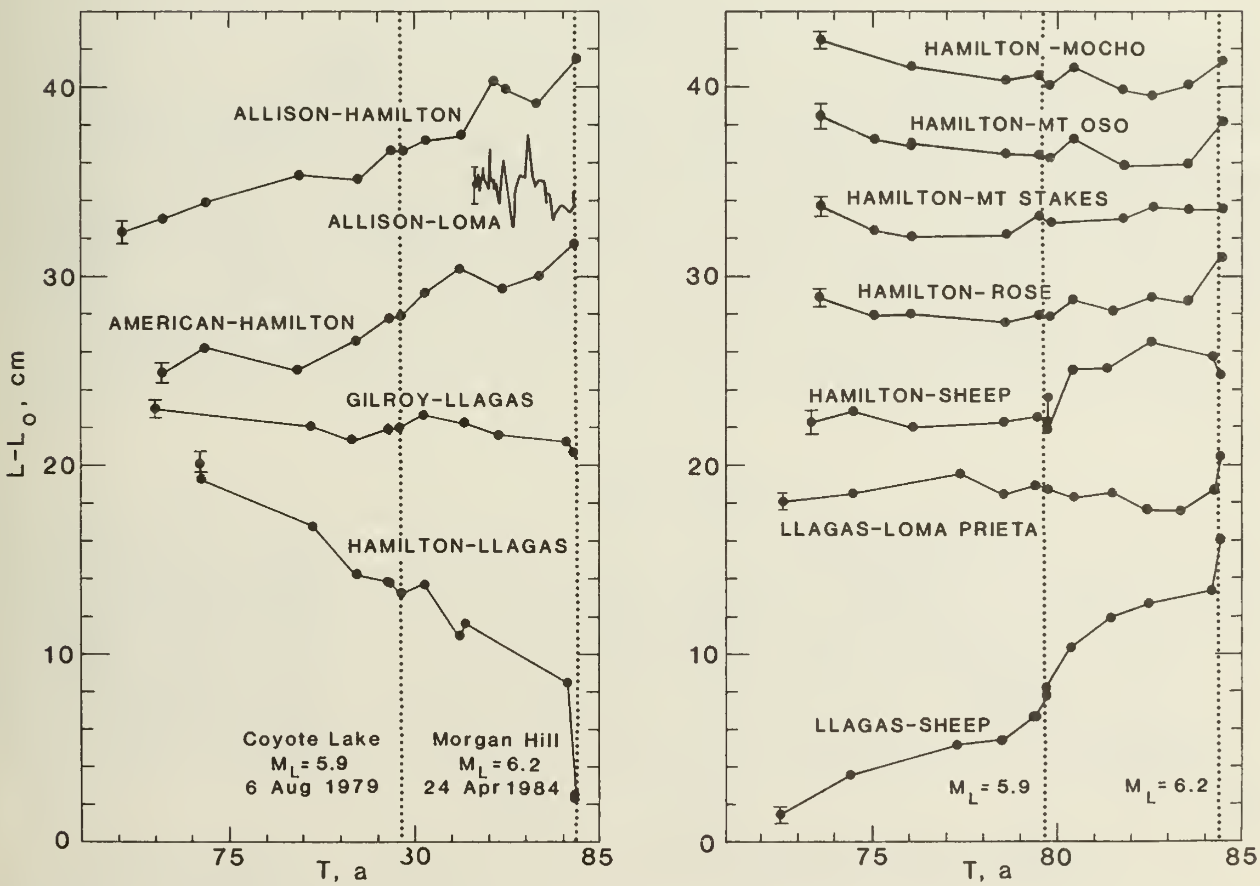

Figure 4. Plot of line length as a function of time. Error bars indicate plus and minus one standard deviation.

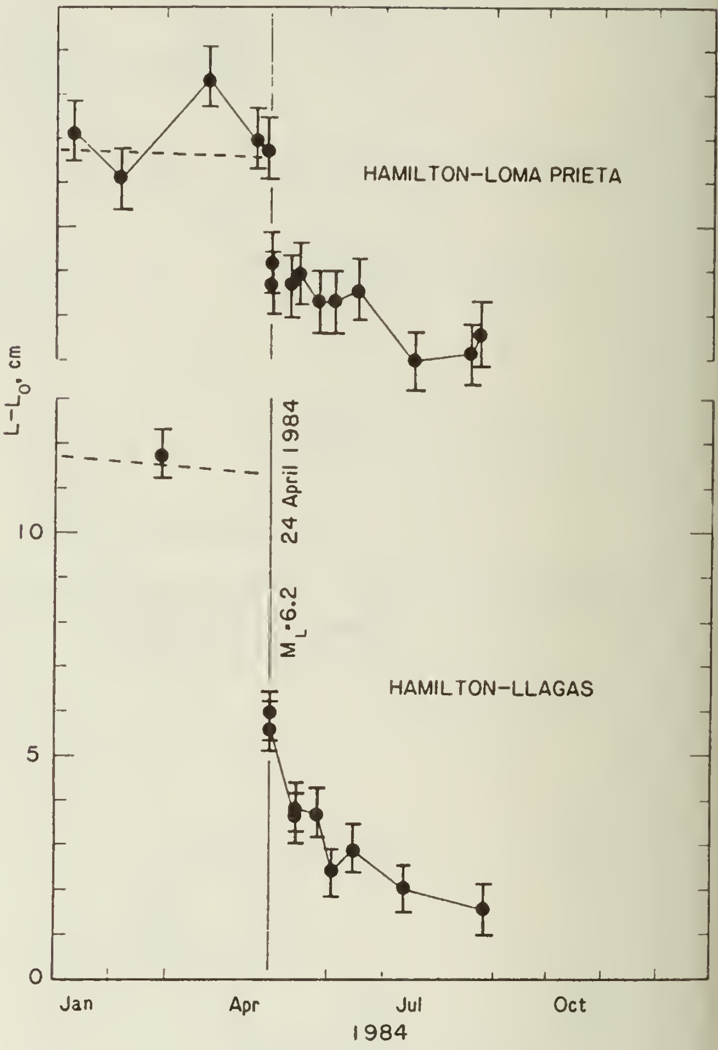

Figure 5. Plot of length of the two lines Hamilton to Llagas and Hamilton to Loma Prieta. Error bars indicate plus and minus one standard deviation. Dashed line is least squares fit to all observations before earthquake.

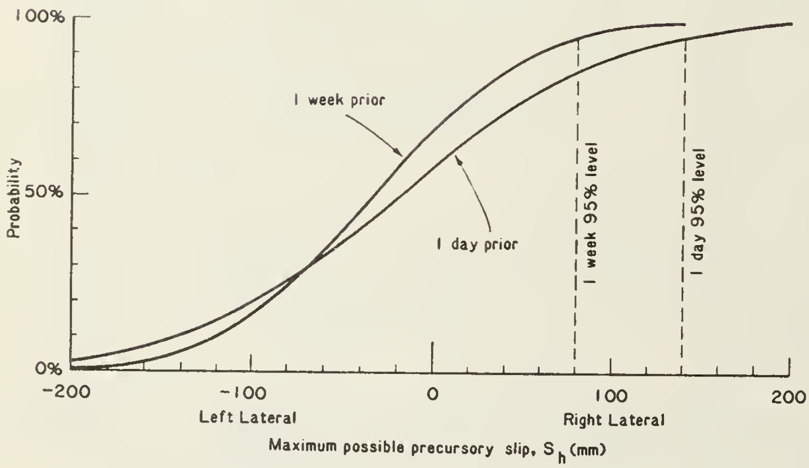

Figure 6. Probability that any precursory slip was less than a specified level, as a function of that level. Vertical dashed lines indicate what the level has to be, in order to be 95% sure that preslip did not exceed it. 1-day-curve is for detection of a preslip event that occurred at least 1 day before the earthquake. 1-week-curve is for detection of a preslip event that occurred at least one week before the earthquake.

"THE APRIL 24, 1984, MORGAN HILL, CALIFORNIA EARTHQUAKE: * THE SEARCH FOR SURFACE FAULTING"

by

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ABSTRACT

Post-earthquake investigation of abundant ground cracks associated with the April 24, 1984, Morgan Hill earthquakes revealed no unequivocal evidence of surface faulting. Cracks in two places in San Felipe Valley were alined with late Quaternary fault traces, but showed no tectonic displacement. Cracks near the southeast end of Anderson Reservoir showed right slip of more than 0.1 m, but were either in or near active landslides or in short zones that had no continuity of displacement or trend along strike in the fault zone. We think the evidence does not demonstrate surface faulting, but we cannot deny the possibility that some cracks were tectonic.

INTRODUCTION

This report summarizes our initial investigations to determine if surface faulting accompanied the April 24, 1984, Morgan Hill, California, earthquakes. Our investigations started the day of the earthquakes and continued through April 27 as we inspected traces of the Calaveras fault mapped by Radbruch-Hall (1974) and Dibblee (1972, 1973), and nearby traces of the Hayward fault. On May 2-4 we checked additional recent traces mapped by D. G. Herd (unpub. maps, 1984) in the epicentral and aftershock zones. We reinvestigated in detail the region at the southeast end of Anderson Reservoir on May 11 and 16. We found no unequivocal evidence for surface faulting from the earthquake, but we cannot eliminate faulting as the origin for some of the many cracks that we found.

OBSERVATIONS

Figures 2-5 shows our routes, sites of primary interest, and the fault trace interpretations of Herd (unpub. maps, 1984), Radbruch-Hall (1974), and Dibblee (1972, 1973). Faults mapped by Herd and Radbruch-Hall were located primarily from geomorphic evidence of recent displacement, whereas those mapped by Dibblee were located also with lithologic, stratigraphic, and structural evidence. Thus some of Dibblee's mapped faults may show little evidence of recent slip. Table 1 records our field observations. Figure 1 shows sites investigated outside of the area of figs. 2-5.

*Text reprinted form U.S. Geological Survey Bulletin 1639; figures adapted from Harms and others, 1984.

1/ U.S. Geological Survey

To distinguish tectonic cracks (the surface expression of deep-seated faults) from nontectonic cracks, we used two guidelines: (1) slip commonly lies in the plane of tectonic cracks, and (2) slip and trend should show broad consistency or regularity along strike for tectonic cracks or zones of tectonic cracks. Some cracks, however, clearly displayed evidence for both factors and at the same time indicated creation by nontectonic processes; thus their origin is uncertain.

Most of the abundant nontectonic cracks in the epicentral and aftershock zones were caused by downslope movement, lurching, differential settling, or other near-surface movement of young deposits or artificial fill. However, the origin of cracks in two areas in San Felipe Valley (sites 25 and 36, fig. 3) and near the southeast end of Anderson Reservoir (sites 64 and 65, fig. 5) is less certain.

The northern of the two sites in San Felipe Valley (site 25) included cracks that were distinct from the surrounding desiccation and differential-settling cracks, but they showed no recognizable tectonic displacement. However, these fractures were aligned with clearly defined fault scarps to the southeast and the northwest. We installed a simple quadrilateral of spikes about 5 m on a side across the cracks on April 25 to help determine if they were of tectonic origin. Four unchanged remeasurements through May 3 across this quadrilateral suggested that the cracks were nontectonic.

Farther south in San Felipe Valley (site 36), north-northwest-trending cracks extended for approximately 10 m along the east shoulder of the paved portion of San Felipe Road and for about 40 m along the unpaved portion of the road. The unpaved portion of the road was graded into surficial alluvium, with no fill added. At the northern end the cracks were most abundant in the coarse-grained deposits of the alluvium (granule to pebble gravel) and ended at the northern contact of this gravel with a finer-grained deposit. We installed a 2-m quadrilateral of nails and stakes at this site on April 25. It also showed no movement through May 3.

Site 64, about 1/2 km west of Cochrane Bridge near the southeast end of Anderson Lake, also exhibited cracks and offset of equivocal tectonic origin. These cracks showed approximately 15 cm of right-lateral displacement across five fractures in a zone about 30 m wide. These breaks crossed Dunne Road at the crest of a ridge and showed generally increasing azimuth from east to west. South of the road (toward the shore), the fractures did not continue in a consistent manner, but became indistinguishable from other randomly oriented cracks. These shore-zone breaks seemed to represent slumping or lateral spreading and were dominantly extensional, with both minor left-lateral and right-lateral components of slip. North of the road, the cracks became extensional and merged with west-trending cracks related to slumping. There was no clear evidence for right-lateral displacement north of the road. Although locally or individually these breaks appeared to be tectonic, they occurred within a broad zone of active landslides and slumps and showed little continuity of trend or displacement within, and none beyond, the landslide-slump region.

West of Cochrane Bridge, on the south side of Anderson Reservoir and on trend with the above cracks, fractures extended about 50 m southeast from Dunne Road (site 65) just west of a driveway up and beyond a steep embankment. These fractures exhibited dominantly right-lateral displacement with minor extension. The cracks did not clearly relate to landsliding. Two fractures, each with more than 0.1 m of right-lateral displacement, crossed Dunne Road on trend with these cracks and may be related to them. However, the two fractures in Dunne Road may be related to local failure of the road fill. No cracks crossed the unvegetated lakeshore northwest of this site, where they would have been very easy to detect. Farther to the southeast, the cracks entered a dense patch of poison oak 20-30 m long, but were not present on the other side of the patch, nor could we find them on benches and slopes farther to the southeast.

CONCLUSIONS

From our evidence, the question of whether surface faulting accompanied the April 24 earthquakes is at this time unanswered. If at all present, tectonic ruptures were short and scattered and showed small offset. Evidence favoring a tectonic origin for the surface breaks in San Felipe Valley and near the southeast end of Anderson Reservoir includes their northwest-southeast orientation and position along mapped or suspected late Quaternary traces in the fault zone and their definite or possible component of right slip. Such evidence convinced Hart (1984) that the ruptures near the southeast end of Anderson Reservoir were tectonic. Evidence against a tectonic origin, however, is that (1) the cracks in San Felipe Valley displayed no or equivocal lateral displacement and those at Anderson Reservoir lay in or near zones of active landslides or slope failure, (2) all four zones (sites 25, 36, 64, and 65) were short and were both internally discontinuous and had clear boundaries on strike that were definitely not faulted (which favors nontectonic origin) and, (3) individual cracks lacked continuity of displacement and trend found elsewhere with tectonic ruptures of small displacement (for example, Brown and Vedder, 1967, Clark and others, 1976; Allen and others, 1972; Fuis, 1982; Sieh, 1982). In sum, we think the evidence does not demonstrate surface faulting associated with the Morgan Hill earthquakes, but we cannot deny the possibility that some cracks were tectonic.

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Table 1. Field observations after the Morgan Hill earthquakes of April 24, 1984 (Data from Harms and others, 1984; locs. 1-78 on fig. 2-5; locs. A-I on fig. 1)

Locality	Feature inspected	Azimuth of crack	Displacement vector	Comment ("Detection level" is minimum visible offset or opening of a crack)	Date investigated (1984)	Investigator
1	Landslide			No unequivocal evidence for movement of old slide.	4-24	SM, KL
2	Dirt road			Road crosses fault zone; no cracks.	4-24	SM, KL
3	Fault lineaments			No displacement at fault mapped by Herd (unpub. maps, 1984).	5-2	JL, SM
4	Quimby Road (paved)			No evidence of displacement at fault/lithologic contact; no movement of large landslide to south.	4-24	SM, KL
5, 6, 8	Fault lineament			No displacement at fault mapped by Herd (unpub. maps, 1984)	5-2	JL, SM
7, 10	Dirt road			No cracks in road that crosses faults.	4-24	SM, KL
12, 13	Tectonic bench			No cracks.	4-24	SM, KL
14	Dirt road			No tectonic cracks on road in fault zone.	5-2	JL, SM
15	Swale			No evidence for movement in apparently tectonic swale.	4-24	SM, KL
16	Dirt road			No offset on road along fault.	5-2	JL, SM
17	Dirt road			Cracks along road appear to be related to desiccation only.	5-2	SM, JL
21	Linear scarp			No cracks.	4-25	RW, MB
22	Dam			No cracks in road to dam.	4-24	JL, JP
				No cracks in dam abutment or in fault zone for 0.6 km to SE.	4-25	RW, MB
23	Dirt road			Cracks in road associated with slumping.	4-25	RW, MB
24	Fault lineament			No cracks crossing fault zone.	5-2	JL, SM
25	Fault lineament			No tectonic cracks.	4-24	JL, JP
	Tectonic swale, quadrilateral			Hairline cracks along tectonic swale. Small quadrilateral installed and measured.	4-25	RW, MB
				Quadrilateral remeasured; no change.	4-26,27, 5-2, 3	JL, SM
26	Fault lineament			Well-defined fault lineation shows no tectonic cracks.	4-25	RW, MB
27	Trails			No cracks on trails surrounding pond.	4-24	JL, JP
28	Fences			Fences appear to be offset, but may have been installed crooked.	4-26	SM, JL
29	Dirt road			No cracks in E-W road in fault zone.	4-25	MC
30	Dirt road			No cracks in road along fault.	5-2	SM, JL
32	San Felipe Ranch (graded fill)			Cracks present in this area, but not tectonic.	4-25	RW
34	Dirt road			No cracks in road.	4-25	MC
35	Dirt road near San Felipe Creek			Many extensional cracks in road near San Felipe Creek and on fill of bridge abutment. A hump in the road was reported here, but was graded before it was investigated. No cracks or compressional features beside the road.	4-24	JL, JP
36	Paved road			No unequivocal tectonic cracks.	4-24	JL, JP
				Narrow zone of fresh discontinuous cracks parallels road. Possibly of tectonic origin.	4-24	JZ, DH
	Quadrilateral			Temporary quadrilateral installed across these cracks. Cracks have been degraded significantly.	4-25	JL, JP, MC, MR, KH
				Measured quadrilateral, no change.	4-26, 27, 5-2, 3	JL, SM
38	Paved road			No cracks in road across fault zone.	4-25	MC
39	Paved road			No cracks in road.	4-25	RW
40	Scarp			Scarp is probably stream cut; no cracks.	4-25	RW
41	Paved road			No tectonic cracks along road.	4-25	RW
42	Paved road			Cracks along trace of Las Animas fault; probably related to slumping.	4-24	JL, JP
44	Roadcut			No throughgoing cracks in gouge of fault zone, but hairline cracks present in dirt road. No lateral displacement.	4-24	JL, JP
	Dirt road and San Felipe Creek			Bedrock and exposed fault gouge contained many fresh cracks, but these exhibited no offset.	4-27	JP

Table 1. (continued)

Locality	Feature inspected	Azimuth of crack	Displacement vector	Comments	Date investigated	Investigator
46	Dirt road and sag pond			Many randomly oriented cracks in road; cracks subparallel with fault exhibited no offset. No cracks in mud surrounding sag pond.	4-27	JP
47	Saddle			No cracks, but detection would be difficult in surrounding vegetation. Detection level about 10 mm.	4-27	JP
48	Dirt road			No offset of road along the fault zone. Detection level about 2 mm.	4-27	JP
49	Dirt road			No cracks with consistent trends on road along fault zone. Detection level about 2 mm.	4-27	JP
50	Dirt road			Many desiccation cracks but no tectonic rupture. Detection level about 2 mm.	4-27	JP
52	Dirt road			Many desiccation cracks, but none consistently oriented parallel to the fault. Detection level about 2 mm on the road, 5 mm off the road.	4-27	JP
53	Paved road	016° (southern) 018° (northern)	5 mm, 085° 5 mm, 091°	Two cracks in road that extend into the shoulder, both with left-lateral displacement.	5-3	KH, MR
54	Paved road	320° (western) 345° (eastern)	40 mm, 280° 40 mm, 075°	Two cracks aligned with mapped fault trace. Right-lateral offset continues off the road, where the detection level is about 20 mm.	4-26	KH
55	Paved road	011°	12 mm, 097° 7 mm, 078° 7.5 mm, 095°	Cracks in road with right-lateral displacement; cracks are aligned with mapped fault trace. They continue off the road, where detection level is about 10 mm.	4-26	KH
56	Dirt driveway (to Jackson Ranch)	325°		Small extensional cracks parallel to fault zone; no lateral displacement.	4-26	KH
57	Paved road	NW-SE	5 mm, 085°	Two cracks display a small amount of right-lateral displacement.	4-25	MC
58	Paved road			No cracks present on road in line with either linear valley or ridge to the southeast.	4-25	MC, KH, MR
59	Paved road	E-W		A crack with right-lateral displacement, probably related to slumping.	4-26	KH
60	Paved road			Wide zone of cracks at northern end of slump block. Zone of cracks is arcuate.	4-26	KH
61	Paved road	175°		Zone of extensional cracks 6 m wide; minor left-lateral component.	4-26	KH
62	Paved road	About 120°	20 mm, 075°	Six cracks across road in zone 20-25 m wide.	4-25	MC
		130°		Set of fresh cracks, trend 130°, with extensional and left-lateral displacement.	4-26	KH
63	Paved road			Abundant cracks across road and south of road; many appear to be related to lateral spreading or slope movement.	4-26	MC
64	Paved road	325° (eastern) 307° 320° 342° (western)	20 mm, 275° 30 mm, 260° 50 mm, 295° 60 mm, 294°	Site of cracking during 1979 Coyote Lake earthquake. Series of large cracks across road. Westernmost two cracks are 8 m apart, trend 170°; eastern of these two cracks shows right-lateral slip of 70 mm at 115°, westernmost shows compression. Six more cracks farther east in zone 30 m wide.	4-25	MC
				Cracks trend 130-160°, with generally increasing azimuth from east to west. Cracks are located on the ridgecrest and are parallel to ridge.	4-25	KH, MR
				Rechecked the painted cracks; no movement.	4-27, 5-3, 5-11, 5-16	KH, MR
64	South of road			Abundant cracks with no dominant trend or sense of displacement. Cracks seem to be related to slumping. Liquefaction occurred between the lake and a closed depression. This closed depression could be fault related, but is more likely caused by slumping. If so, the liquefaction occurred along the edge of this slump block.	4-25, 5-3	KH, MR
	North of road			Cracks continue for 10-15 m before they are dominated by more westerly trending cracks. These cracks define several small slump blocks, but no lateral cracks were found at the western end of these slump blocks.	4-25	KH, MR
				Cracks curve to the west, stepping right for 75-100 m. Overall trend is about 350°. These cracks show <50 mm extension and no apparent lateral displacement.	5-11, 5-16	KH
65	Paved road	300-310°	25-50 mm, 255°	Distinctive cracks extend about 50 m SE of road.	5-3	KH

Table 1. (continued)

Locality	Feature inspected	Azimuth of crack	Displacement vector	Comments	Date investigated	Investigator
			120 mm, 095° 100 mm, 105°	Two cracks across road. Northernmost has 120 mm right slip at 095°; southern crack has 100 mm right slip at 105°. 1/2 to 2 m long, left-stepping en echelon cracks lie on trend to the SE at top of roadcut. These cracks enter heavy brush about 30 m SE of top of cut. No cracks 50-60 m from cut on other side of brush.	5-4	MC
67	Scarp			No cracks along scarp and notch. Detection level about 5 mm.	5-4	MC
68	Corral and barn			No cracks on trend with those seen at site 65. Many dilation cracks trending 90°-205° with 50 mm extension and 50 mm down on NE side. They appear to relate to free faces to the N and E.	5-4	MC
69	Jackson Oaks tract			A prominent crack begins at the ridgecrest; probably related to slope failure.	4-25	SM
				Crack trends E-W and shows no relation to landslide movement. The cracks could be due to differential settling of fill along a grading contact.	5-16	EH
70	Notch			No rupture in notch. 2-4 mm detection limit in dirt road, 5-15 mm off road.	4-24	MC, KH
71	Notch			No rupture in grassy valley and notch. 5-15 mm detection limit.	4-24	MC, KH
72	Notch			No rupture in notch. 2-4 mm detection limit in dirt road, 5-15 mm limit in grass.	4-24	MC, KH
73	Dirt road			No ruptures on road or fields along mapped trace of fault. 5-15 mm detection limit in fields, 2-4 mm detection limit on dirt roads.	4-24	MC, KH
74	Linear flat			No rupture on small linear flat.	4-24	MC, KH
75	Lake shore			Cracks trend 165° with 110 mm extension. No lateral component of slip present.	5-3	KH, MR
76	Linear valley	160°	10-20 mm, 250°	A long continuous crack follows this linear valley for 50 m.	5-16	KH
77	Linear valley	145°	10 mm, 235°	A crack parallels the road and the linear valley for 30-35 m.	5-16	KH
78	Lakeshore			Cracks show 35 mm left-lateral offset and 30 mm extension. This is part of a slump toward the lake, on the NW side of a young fan deposit.	5-3	KH, MR
A	Paved road			No cracks on trace of Hayward fault.	4-25	KH, MJ
B	Paved road			No cracks on trace of Hayward fault.	4-26	JL, SM
C	Dam			Cracks due to slumping, but no tectonic offsets.	5-2	JL, SM
D	Fault lineation			No cracks. Detection level about 3 mm.	5-2	JL, SM
E	Paved road			No fresh cracks on left-stepping en echelon cracks in road.	5-2	JL, SM
G	Paved road	146°	1 mm, 128°	Some fresh cracks at north side of road, extending from older cracks.	4-27	MR
H	Paved road			Fresh cracks on SE side of the road with a net right-lateral offset of 3.5 mm. On the NW side of the road, fresh cracks show 2 mm of right-lateral displacement. Creepmeter at this site showed 13 mm of coseismic slip.	4-27	MR
I	Paved road			No fresh tectonic cracks.	4-27	MR

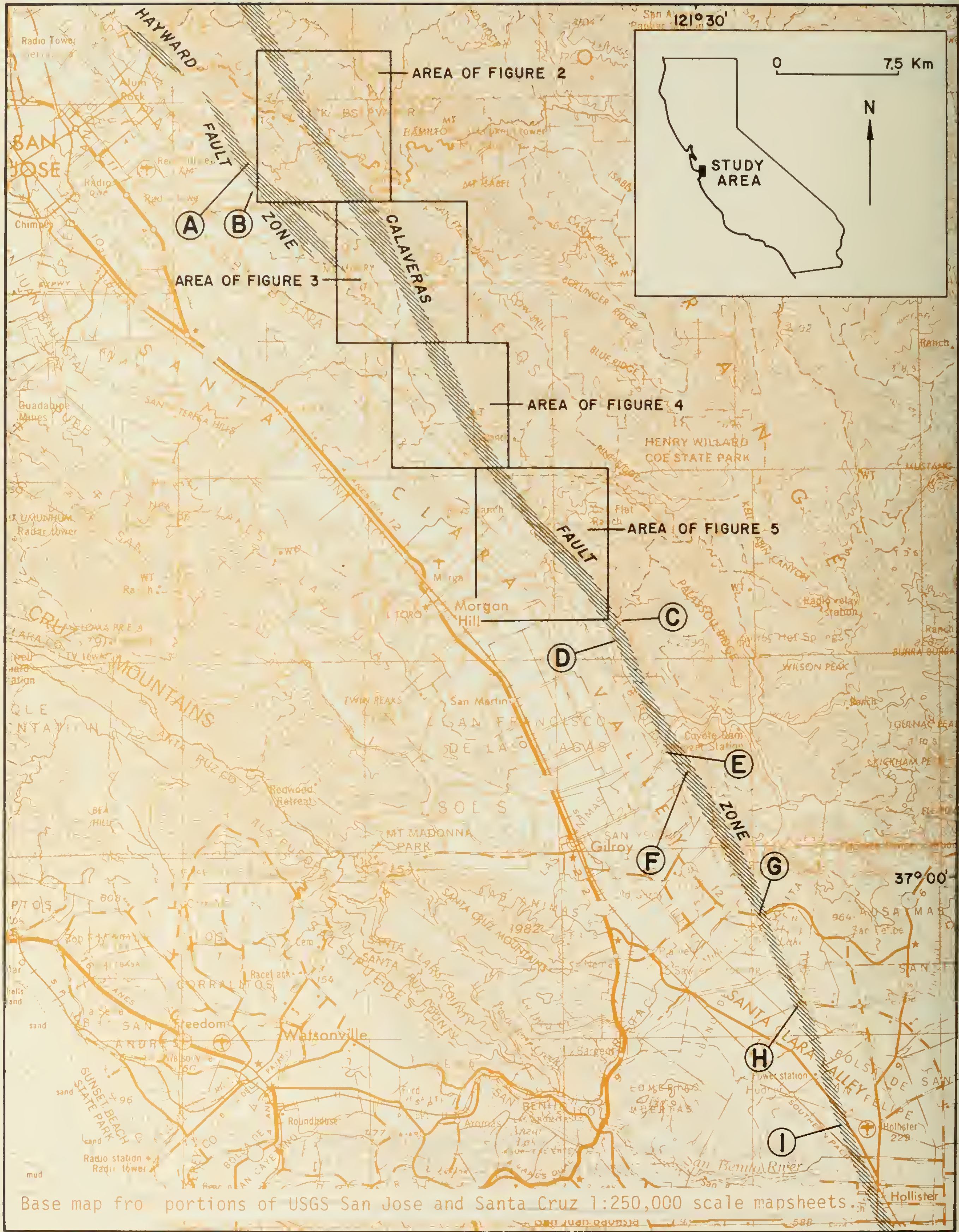
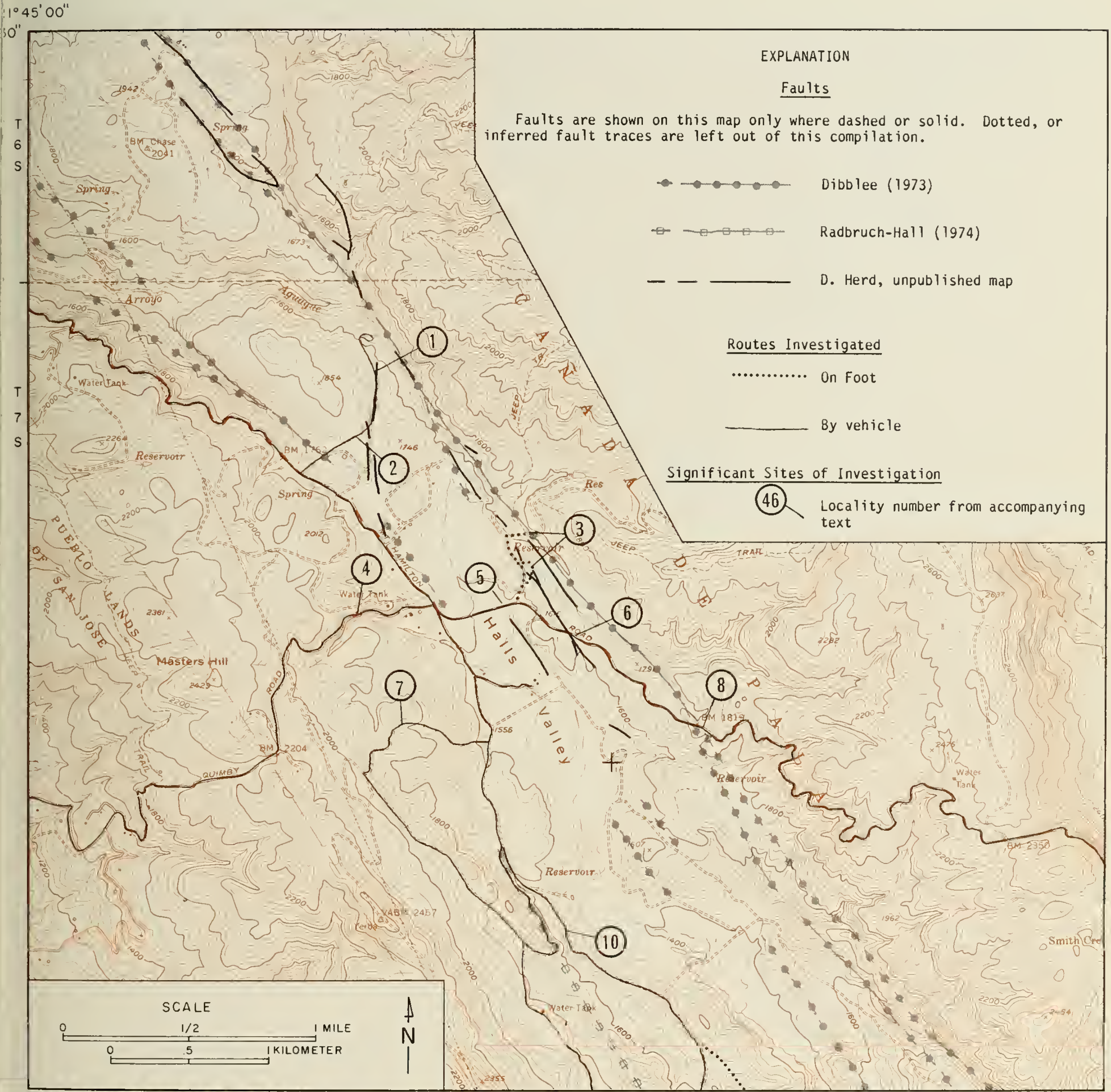
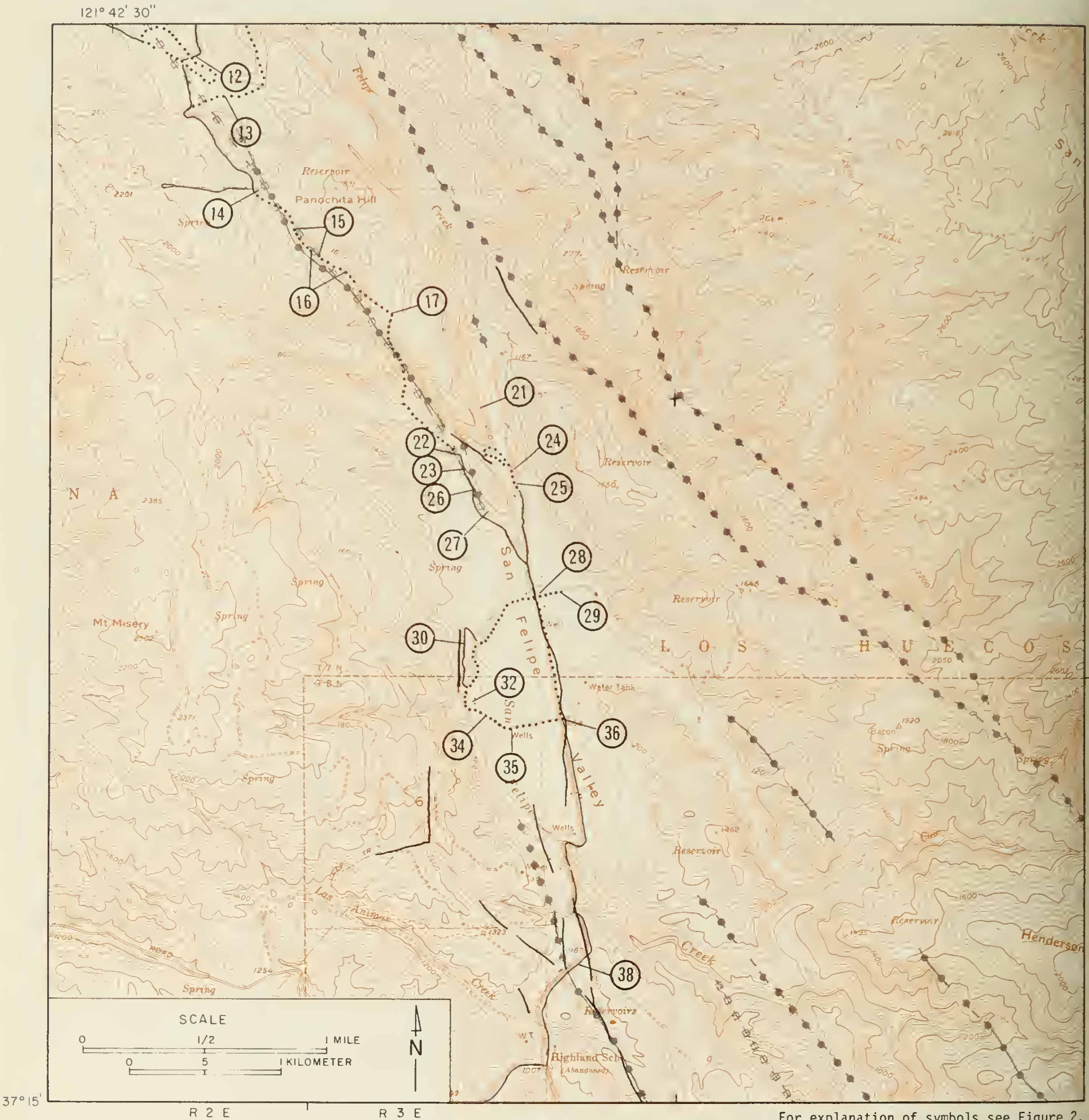


Figure 1. Map showing sites investigated in Calaveras and Hayward fault zones that lie beyond the aftershock zone of the Morgan Hill earthquakes.



BASE REDUCED FROM U.S.G.S. 7.5' QUAD
(Lick Observatory)

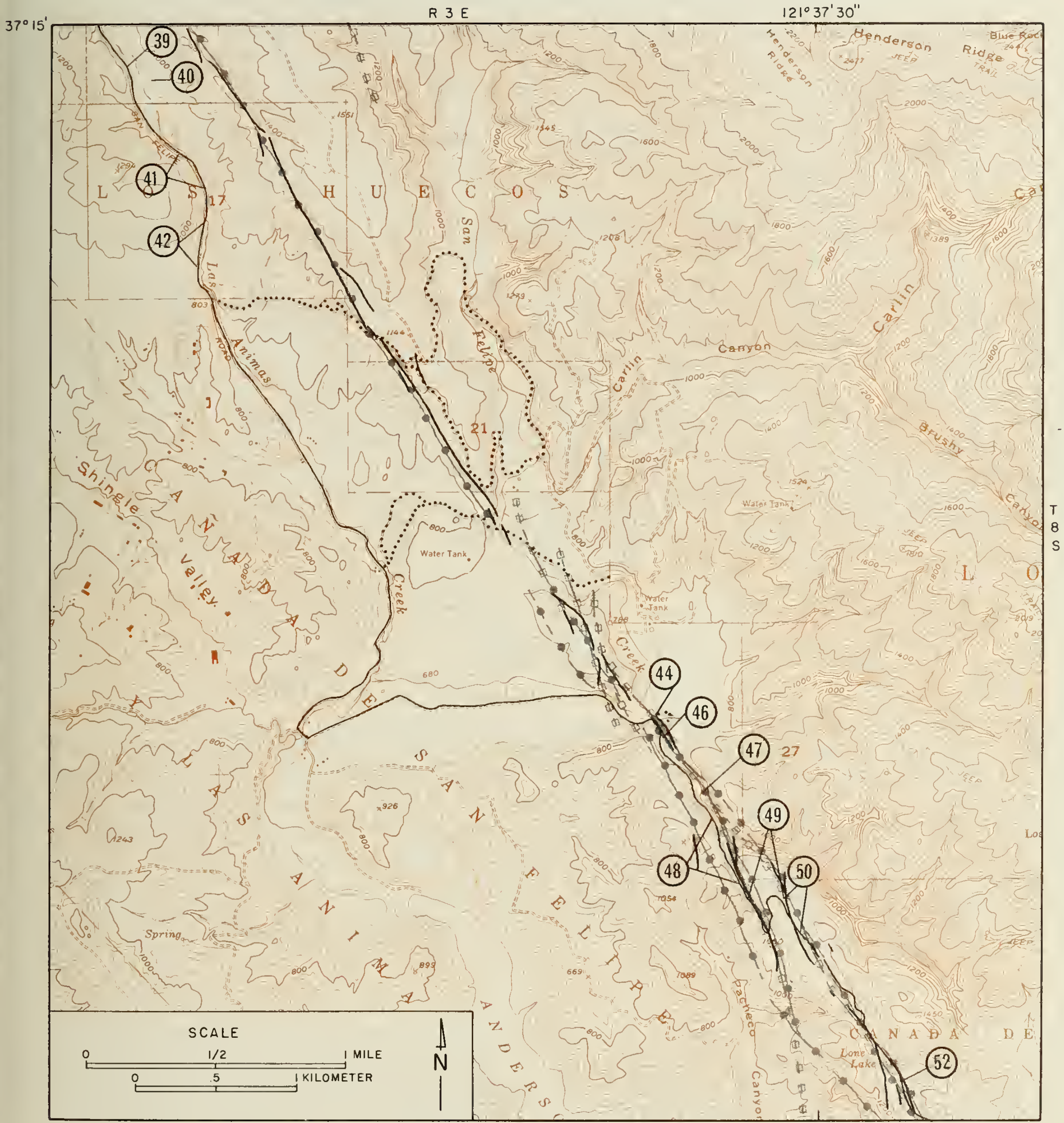
Figure 2.



BASE REDUCED FROM USGS 7.5' QUAD. (Lick Observatory)

For explanation of symbols see Figure 2.

Figure 3.



BASE MOSAICKED AND REDUCED FROM USGS 7.5' QUADS (Morgan Hill and Mt Sizer)

For explanation of symbols see Figure 2.

Figure 4.


121°37'30"
R 3 E
R 4 E
T 9 S
LAS ANIMAS
ANDERSON
PUEBLO LANDS OF LAKE SAN JOSE
OJO DE AGUA
SANTA CLARA
DE LA COCHE
SAN FRANCISCO DE LAS LLAGAS
Twin Lakes
Tule Lake
Packwood
Creek
Samson
Samson Canyon
Canyon
Ridge
Spring
Oak Flat Ranch
Schoolh
Finley Ridge
Clarks Canyon
Cochrane Bridge
Coyote Creek
Mud Lake
Otis
Swimming Pool
Water Tank
SCALE
0 1/2 1 MILE
0 .5 1 KILOMETER
N
37°07'30"
BASE MOSAICKED AND REDUCED FROM USGS 7.5' QUADS
(Morgan Hill and Mt Sizer)
For explanation of symbols see Figure

Figure 5.

EVIDENCE OF SURFACE FAULTING ASSOCIATED WITH MORGAN HILL EARTHQUAKE OF APRIL 24, 1984

by

Earl W. Hart[1/]

ABSTRACT

Discontinuous surface rupture occurred along the Calaveras fault during and shortly after the Morgan Hill earthquake of April 24, 1984. As much as 20 cm of right-lateral slip may have occurred coseismically at the southeast end of Anderson Lake, although it is possible that these ruptures may be due to landsliding. Minor right-slip also was observed at several other locations along the fault. However, rupture at these other localities was partly equivocal and partly occurred as afterslip. The discontinuous and minor surface ruptures associated with the Morgan Hill earthquake partly overlap with and are similar in style, magnitude, and timing to those ruptures associated with the August 6, 1979 Coyote Lake earthquake.

INTRODUCTION

The Calaveras fault is a major element of the highly active San Andreas fault system (Jennings, 1975). Based on its generally youthful surface expression, historic fault creep, seismicity, and geodetic strain, the Calaveras fault is considered active over a length of more than 120 km from San Ramon to Hollister (Wesson and others, 1975; Herd, 1979; Hart and others, 1981). It is estimated that about 20 km of right-lateral slip has occurred along the fault in the last 3.6 my., giving an average slip-rate of 5.6 mm/year during that period (Page, 1982). Several historically damaging earthquakes have been attributed to the Calaveras fault (Toppozada and others, 1981; Toppozada, this volume).

In spite of the high-level and well-defined zone of seismicity, the recent traces of the Calaveras fault are well defined only locally. This is particularly true in the mountainous areas north of Coyote Lake where segments of the fault are partly obscured by massive landslides and lateral spreading of ridges. Elsewhere, surface faulting appears to be distributed as multiple strands across a wide zone, possibly as a result of numerous right or left steps and changes in azimuth along the fault (Figure 1). The complexities of surface faulting, as well as disagreements in the locations of recently active traces, are demonstrated in the Halls Valley-Morgan Hill area by the mapping of

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Dibblee (1973), Radbruch-Hall (1974), Wagner (1978), D. G. Herd (in Harms and others, 1984), and W. A. Bryant (in CDMG, 1982).

Historic surface rupture of the Calaveras fault may have occurred during the 1861 earthquake in San Ramon Valley (Trask, 1864) and the 1897 earthquake near Gilroy (Toppozada and others, 1981), but the evidence for this is poorly documented. Minor, discontinuous rupture was associated with the Coyote Lake earthquake of 1979 (Armstrong, 1979; Cotton, 1979; Lee and others, 1979; Rogers and others, 1982), from Hollister possibly as far north as Anderson Lake (Figure 1). However, the Anderson Lake ruptures of 1979 (coincident with Locality 2 in this paper) may have been caused by landsliding, and most of the other ruptures were the result of afterslip.

Much of the documented surface rupture on the Calaveras fault apparently occurs as episodic creep between Hollister and Coyote Lake. Long-term creep rates are variable from place to place, but exceed 1 cm/year locally (Herd, 1979; Armstrong and others, 1980; Schulz and others, 1982). A maximum slip-rate of 1.6 cm/year was determined by an alignment survey just south of Coyote Lake (Harsh and Burford, 1982). Other creep localities have been inferred to the north (Cochrane Bridge, Halls Valley, Sunol, Dublin), but surface rupture has not been verified by ground cracks or offset structures.

The purposes of this paper are: 1) to summarize the evidence for surface fault rupture that occurred in association with the April 24 earthquake and 2) to attempt to distinguish between coseismic rupture and afterslip. Some comparisons also are made with the minor fault rupture associated with the August 6, 1979 earthquake.

EVIDENCE OF SURFACE FAULTING

Immediately following the April 24, 1984 earthquake, geologists from the Division of Mines and Geology were dispatched to the field. An immediate response was necessary to map any surface faulting associated with the earthquake before the evidence was obscured or destroyed and to distinguish coseismic rupture from afterslip. An initial summary of this work is presented by Hart (1984). Similar responses were made by the U.S. Geological Survey and others, whose results are largely summarized by Harms and others (1984 and this volume), Galehouse and Brown (1984), and Schulz (this volume).

Many recently active fault strands of the Calaveras fault were carefully checked, but very little evidence of tectonic rupture was observed. This was surprising considering the magnitude of the earthquake (M6.2). Possible discontinuous surface faulting (all right-lateral) was identified at only seven localities over a distance of 41 km, from San Felipe Valley to Shore Road north of Hollister (Figure 1). Evidence present at these localities is summarized in Table 1 and discussed below. At each locality, fault rupture was either minor or equivocal--or both. It is unclear if coseismic surface faulting occurred and differences in opinion exist (Harms and others, this volume; Hart, 1984). That afterslip occurred is fairly definite at Locality 6, although the locality lies well south of the aftershock zone (Figure 1 and Table 1). Localities where no evidence of surface faulting was observed are identified with an "N" in Figure 1.

The only evidence of significant coseismic surface faulting was noted at Localities 2 and 3 (Figure 2), where about 16 and 20 cm of right-lateral displacement were observed (Figure 2, Table 1). Both rupture zones have been modified by downslope movements and conceivably may be caused entirely by landsliding. In my opinion, however, the right-lateral displacements at both localities are better explained by fault rupture than by downslope movements.

The northwest-trending zone of fissures at Locality 2 occurred within a large, complex landslide (Dibblee, 1973; Wagner, 1978; Figure 2). As pointed out in Table 1, the fissure zone is about 30 m wide and provides clear evidence of right-lateral displacement across the paved extension of E. Dunne Avenue. A sketch of the fissure zone, showing a cumulative offset of roughly 16 cm, is shown in Figure 3. Although the fissures at Locality 2 can be traced to the southeast for about 50 m as a zone of vaguely left-stepping cracks to the west edge of a closed depression, the evidence of fault rupture is substantially masked by lateral spreading of the ground.

The crack zone can be traced with difficulty, but more or less continuously, for about 100 to 150 m in a N30°W direction (Figure 2). (Harms and others, p. 106, 1984, state the trend to be about N10°W.) In places, newly formed scarplets and fissures peel-off to the west from the northwest-trending fissure zone. These west-curving features show a maximum of 0.5 m vertical and extensional displacement and locally coincide with older landslide scarps (schematically shown on Figure 2). Although only limited parts of this landslide were checked for ground rupture following the April 24 earthquake, other active landsliding apparently occurred only to the west of the inferred fault zone (Figure 2). No significant cracks, scarps, or other evidence of landsliding were noted along the paved road for a distance of 0.5 km east of Locality 2. If the right-lateral displacements at Locality 2 represent the west margin of a landslide, then other features suggestive of southeastward-directed slope-movement presumably should have been observed east of Locality 2. On the other hand, if the active sliding to

the west caused the fissures of Locality 2, then predominantly extensional or left-lateral ruptures should have been developed. In view of the data at hand, it appears that faulting is the most likely cause of the right-lateral offsets of the pavement at Locality 2.

The two distinct cracks at Locality 3, described in Table 1, show a total of about 20 cm of right-lateral displacement in a N75° to 85°W direction with very little extension and no vertical displacement. The cracks extended southeastward through sheared serpentinite and overlying colluvium of the road cut (photo 2). Because of the westerly trend of the cracks and the presence of loose colluvium in the reentrant gully southwest of the cracks, the right-lateral displacement could be attributed solely to downslope movements. However, no matching set of landslide cracks with left-lateral slip were observed along the road to the southwest on the other side of the gully or beyond. The fissures in the roadcut extend upslope around a severely shattered serpentinite knob 15 to 20 meters from the road and onto the crest of a small spur for another 30 to 40 meters to the southeast. The fissure zone, which is about 20 meters wide near the knob, cannot be traced to the southeast (Figure 2; W. A. Bryant, field notes; Harms and others, 1984). Most of the fissures on the spur show purely extensional openings and are clearly the result of shallow downslope movements of the soil to the southwest and northeast. However, left-stepping fissures were noted locally and evidence of right-lateral displacement to 4 and 4.5 cm was measured on separate fissures on each side of the spur crest. Although the 4 cm of right-slip noted on a fissure along the west side of the spur crest conceivably could have been caused by slip along the margin of a landslide in the adjacent gully, the associated fissures indicate downslope movements to the southwest. The movement does not appear to be related to deeper sliding. Right-lateral slip also was measured on a distinct set of northwest-trending fissures just east of the ridge crest. The fact that this fissure zone was roughly parallel to the slope contour and above a new landslide scarp suggests a tectonic origin. Considering the obscuring effects of lateral spreading fissures which formed on the spur, the 8 to 8.5 cm of right-slip noted in the fissure zone certainly is consistent with the magnitude and sense of inferred faulting in the paved road to the northwest.

Other cracks with as much as 11 cm of extensional opening and a N15°W-trend were reported along the shoreline northwest of Locality 3 (Harms and others, 1984). Although no evidence of slip was reported at this locality, the cracks lie roughly on trend with and between Localities 2 and 3 (Figure 2). These cracks may be associated with apparent fissures in the steep bedrock bluff that I saw from a distance on April 26, but did not visit.

In addition to Localities 2 and 3, minor coseismic rupture also may have occurred at Localities 1 and 4 (Table 1) and possibly elsewhere within the aftershock zone (Harms and others, 1984), but all of that evidence is highly equivocal. Afterslip had not been reported at any

locality between Coyote Dam and Halls Valley by May 16 (later at some localities), which is unusual for strike slip faults of the San Andreas system. Right-lateral afterslip reportedly occurred at Locality 6 (Table 1; Schulz, this volume), and probably accounted for the minor faulting at Localities 5 and 7 (Table 1). These same localities are known creep localities and also showed afterslip (also minor coseismic slip at Locality 6) associated with the August 6, 1979 earthquake (Lee and others, 1979; Armstrong, 1979; Cotton and others, 1979; Rogers and others, 1982). Because the April 24, 1984 ruptures at Localities 5 to 7 were south of the aftershock zone and were discontinuous, it seems likely that this slip was triggered by shaking that locally released strain that had accumulated along the fault.

CONCLUSIONS AND DISCUSSION

Only discontinuous and minor surface faulting occurred along the Calaveras fault in association with the April 24, 1984 earthquake. Just how discontinuous and minor is perhaps debatable, but no surface faulting was reported in the epicentral area or along most fault segments within the aftershock zone. Significant coseismic surface rupture was noted at the southeast end of Anderson Lake (Localities 2 and 3), where a maximum right-slip of 20 cm occurred. Although this rupture may have been caused by landsliding (Harms and others, this volume), I believe the evidence is more supportive of fault rupture. Very minor coseismic faulting also may have occurred elsewhere (e.g. Localities 1 and 4) and some may have been overlooked.

Afterslip of 12.9 mm (right-lateral sense) occurred at Shore Road (Locality 6) shortly after the earthquake (Schulz, this volume). This probably was a creep event triggered by shaking, as the location was well beyond the aftershock zone. Very minor rupture, either coseismic slip or afterslip also occurred at Localities 5 and 7, which are south of the aftershock zone. Surprisingly, no afterslip was evidenced by surface rupture within the aftershock zone as of May 16, although no concerted effort was made to re-observe critical localities for this phenomenon, except at Shore Road where a creepmeter is located (Schulz, this volume). (Also see Prescott in this volume for evidence of possible creep in Halls Valley, based on geodetic measurements.) Afterslip is very common on strike-slip faults and has been observed after earthquakes on the Calaveras fault (Rogers and others), Greenville fault (Hart, unpublished mapping), and other faults in California.

The discontinuity and sparse distribution of minor surface faulting associated with the April 24, 1984 earthquake appear at first glance to be somewhat unusual, but are not unique. Similar rupture has been observed on the Calaveras fault after the Coyote Lake earthquake of 1979 or the Greenville fault after the Livermore earthquake of 1980. No surface rupture occurred in the epicentral areas for these events, nor

did epicentral surface rupture occur during the 1979 earthquake on the Imperial fault.

Subsurface rupture from the April 24, 1984 earthquake reportedly was initiated at a depth of 9 km and propagated mainly southward for 25 km in a zone 4 to 10 km deep (Bakun and others, 1984). Although right-lateral displacement of about 42 cm has been suggested at depth (Bakun and others), apparently little of the rupture reached the surface as discrete ruptures during or immediately after the April 24, 1984 earthquake. The reasons why fault rupture may not have propagated to the surface are not well understood, but may relate to the discontinuous and complex distribution of recently active faults mapped at the surface (see Introduction). It is speculated that the upward propagating rupture was intercepted by and distributed within a complex zone of faults and fault slices. Part of the strain may have been released as minor slip along individual fault strands, which may not have been checked for rupture (or even recognized) or as other deformation. Part also may be stored elastically for later release, either as coseismic or aseismic slip.

Massive landslides, which are so abundant north of Coyote Dam, also may have played a role in obscuring evidence of surface faulting. In part, the landslides may have diffused or inhibited the upward propagation of faulting. Where faulting may have propagated to the surface, evidence of that rupture may have been largely masked by downslope movements (e.g. at Localities 2 and 3). Viewed in this light, it would be surprising if surface fault rupture was continuous in the Anderson Lake area.

Another factor that may bear on the distribution of coseismic rupture is the "late pulse...seismic radiation" that apparently originated near the southern end of the subsurface rupture zone and propagated northward (Bakun and others, 1984). Although the relationship of this pulse to surface faulting is unclear, the proximity of the pulse source close to the inferred fault rupture is suggestive.

Finally, a relationship may also exist between surface faulting and other types of ground failures (landslides, liquefaction, rockfalls, ridgetop shattering, lateral spreading) observed at the southeast Anderson Lake area. These shaking failures and reported structural damage were clearly most severe and abundant within one kilometer of the inferred fault rupture. The secondary failures and damage decreased gradually north and south along the fault and diminished rapidly in either direction normal to the fault. Additional data on shaking intensity and damage are reported in other papers in this volume.

ACKNOWLEDGEMENTS

Field assistance was provided by W.A. Bryant, G.B. Saucedo, D.L. Wagner, R.H. Sydnor, and P. Wong of DMG, who made observations on April 24, 25, 26, 28, and May 26, 1984. Early observations and information also were provided orally by J.B. Baker of William F. Jones, Inc., as well as by K.K. Harms, M.M. Clark, M.J. Rymer, S.S. Schulz, J.J. Lienkaemper, P.W. Harsh, and others of the U.S.G.S. This report was reviewed by M.M. Clark of the USGS and R.H. Sydnor and W. A. Bryant of DMG. The assistance of these people is gratefully acknowledged.

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Table 1. Localities where evidence of fault rupture was observed after the April 24, 1984, Morgan Hill Earthquake (see Figure 1 for locations). Descriptions are based on observations of E.W. Hart, except where noted.

1. 2mm of right-lateral offset along a re-opened crack in the southeast concrete bridge abutment where San Felipe Road crosses San Felipe Creek. Previous crack (patched) had 2.4 cm of right-lateral offset. Observed April 24, and May 2. Cracks in road pavement and fill to north; not clearly tectonic.

2. 30 m-wide zone of seven well-defined sets of NW-trending cracks (mostly left-stepping) in a paved road 0.7 km northwest of Cochrane Bridge on the NE side of Anderson Lake. Right-lateral slip was 0.5 to 6 cm on individual crack sets with about 16 cm of total right slip. Although the crack zone lies within an active landslide, cracks can be followed about 100-150 m diagonally upslope in a N30°W direction. Poorly defined zone of left-stepping cracks in the soil also can be followed about 50 m to the SE into an area of lateral spreading next to a sag pond. Cracks painted April 26--no afterslip. Observed April 24 (D.L. Wagner and G.B. Saucedo, DMG) and April 25, April 26, and May 1. At this locality 0.5 cm of right-lateral slip was observed along a well-defined set of left-stepping cracks after the August 1979 earthquake.

3. Two parallel N75° to 85°W-trending cracks about 3 m apart in paved East Dunne Avenue, 0.4 km west of Cochrane Bridge. Right-lateral slip was 8 and 12 cm on the SW and NE cracks, respectively. Cracks terminated to the NW in a slumped road shoulder. A fissure zone 20 m wide was traced to the SE 50-60 m across the crest of a spur where the zone is 20 m wide. Cracks on both sides of the narrow ridge-crest show 4 to 4.5 cm of right-lateral slip; other cracks are purely extensional and largely due to shaking. Cracks painted -- no afterslip as of May 26 (W.A. Bryant, p.c.). Observed April 25, April 26 and May 1. Similar cracks with minor right-lateral extension were also observed in pavement following the 1979 earth- quake.

4. Minor N30°W-trending crack in an old concrete ford-crossing on the west side of Coyote Creek. The crack shows about 1 mm of new right-lateral slip on an older crack with 2 mm of previous slip. This could be a shaking effect, but the crack lies on the eastern trace of the fault. Observed May 2.

5. Old left-stepping cracks in the pavement of Leavesley Road at Roop Road re-opened 1 to 5 mm by right-lateral extension. Other old left-stepping cracks in Leavesley Road pavement 160 and 240 m to the south also re-opened 1 to 5 mm. Observed May 2. Observations on April 25 (W.A. Bryant) indicated only slight reopening of cracks and new hairline crack at Roop Road and no evidence that old cracks to south were reopened. Afterslip or triggered creep likely. The localities were previously ruptured in the August 1979 earthquake and by on-going fault creep.

6. Creepmeter at Shore Road recorded 12.9 mm of right-lateral slip in 18 hours, beginning 6 hours after the April 24 earthquake. Fresh cracks were observed in the soil shoulder of the road April 25. 8.3 mm of coseismic and afterslip occurred at the site and road cracks developed after the August 6, 1979 earthquake (S. Schulz, this volume).

7. Cracks in pavement of Highway 152 slightly reopened and fresh hairline cracks formed in soil shoulders; minor right-lateral slip. Observed April 25 (Galehouse and Brown, 1984) and April 27 (Harms and others, 1984). However, no fresh cracks noted in soil shoulder by W.A. Bryant on April 25.

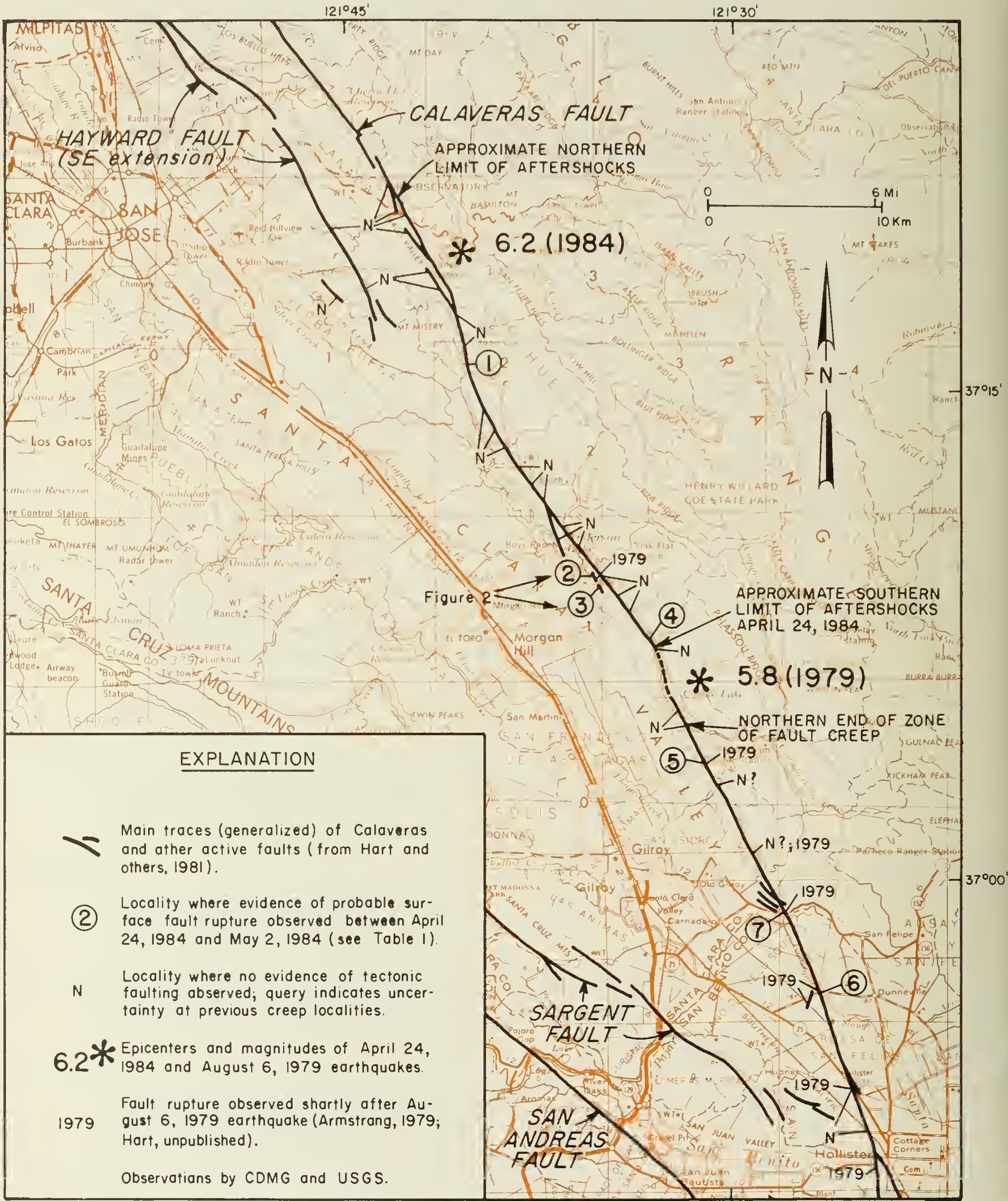
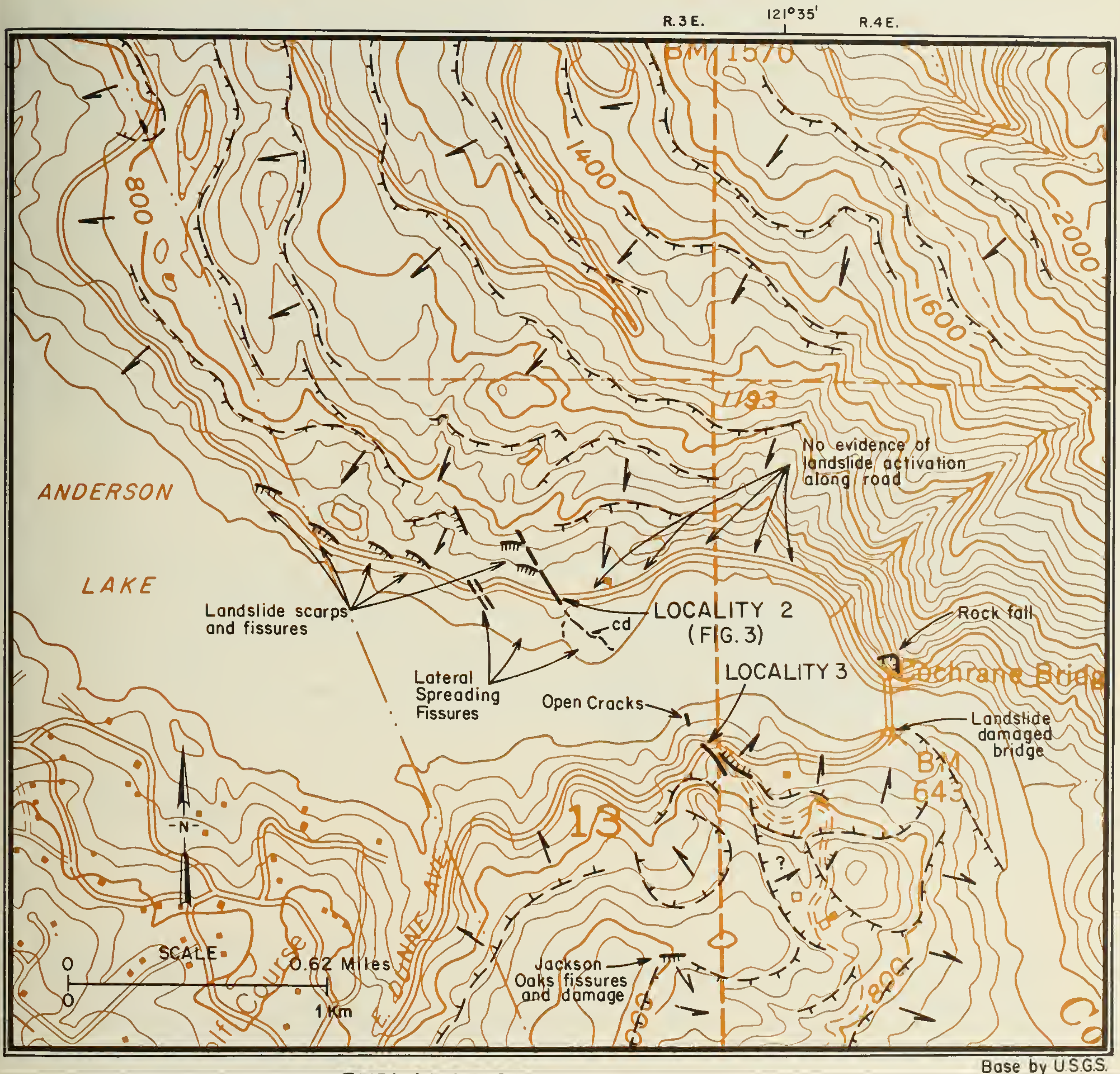


Figure 1. Locations of probable surface faulting associated with the April 24, 1984 earthquake.



EXPLANATION

Fissure zones of probable fault origin

Activated landslide scarps and associated fissures; tick marks on down-dropped side.

Principal scarps and apparent direction of movement from previous landsliding

cd Closed depression

Figure 2. Probable fault rupture and landslides fissure activated during April 24, 1984 earthquake in landslides east of Morgan Hill, Mt. Sizer 7.5 minute quadrangle. Features are partly generalized and incompletely mapped.

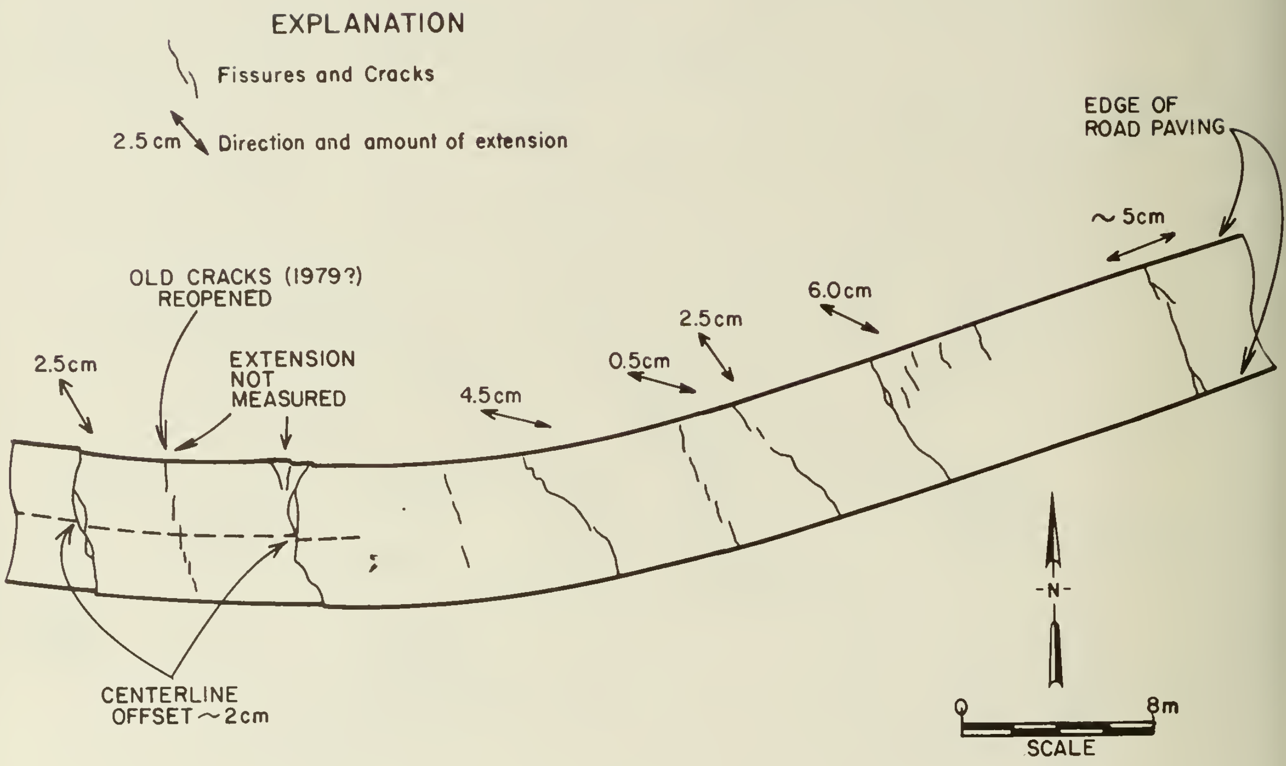


Figure 3. Generalized sketch of fissures and cracks in pavement of E. Dunne Avenue at Locality 2. Approximately 16 cm of cumulative right-slip can be calculated across zone assuming a N30°W trend of the fissure zone (Figure 2). Most fissures have been modified by east-west extension due to lateral spreading of the road.

Photo 1. Two well-defined sets of northwest-trending cracks in East Dunne Ave. 0.4 km northwest of Cochrane Bridge (Locality 2, Figure 1). Right-lateral slip of 6 cm and 2.5 cm was measured on left and right sets, which are parts of a 30 m-wide zone of cracks with cumulative offset of about 16 cm. Although within a landslide, the cracks are believed to be due mainly to faulting.

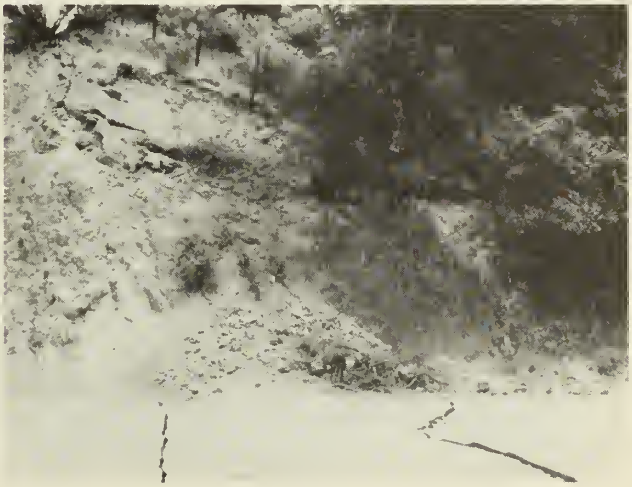


Photo 2. View to east of two N75-85°W-trending cracks in East Dunne Avenue 0.4 km west of Cochrane Bridge (Locality 3, Figure 1). Left and right cracks show 12 and 8 cm of right-lateral offset, respectively. The crack zone extends through serpentinite and colluvium in the road cut to a small spur.

Photo 3. Detail of a portion of the right crack shown in Photo 2. Note rhombic extension of 8 cm. White line was painted to monitor possible afterslip, which was obscured as late as May 26.

TRIGGERED CREEP NEAR HOLLISTER AFTER THE APRIL 24, 1984, MORGAN HILL, CALIFORNIA, EARTHQUAKE

by

Sandra S. Schulz [1/]

ABSTRACT

During the April 24, 1984, Morgan Hill earthquake (M_L = 6.2) on the Calaveras fault, a rod creepmeter at Shore Road on the same fault but 50 km southeast of the epicenter recorded a small right-lateral step, with total afterslip of 12.9 mm during the next 18 hours. The morning after the earthquake, fresh cracks were visible near the creepmeter in the dirt shoulders of Shore Road. No other fresh cracks were found between Shore Road and Hollister, 10 km southeast, and three rod creepmeters in Hollister showed no unusual movement since January 1984. The large afterslip at Shore Road is unusual considering no unequivocal tectonic surface faulting occurred in the epicentral area. The Shore Road site may be unusually sensitive to regional strain and/or stress changes.

INTRODUCTION

The U.S. Geological Survey operates four creepmeters northeast of Hollister on the Calaveras fault (Figure 1). The northernmost of the four sites (Shore Road) has shown unusual sensitivity to regional strain and/or stress by recording triggered creep in response to two distant moderate earthquakes on the same fault, the Morgan Hill earthquake of April 24, 1984, and the Coyote Lake earthquake of August 6, 1979. After the Morgan Hill earthquake, surface fractures were found near Shore Road, 50 km from the earthquake's epicenter.

TRIGGERED CREEP AT SHORE ROAD

Shore Road crosses a trace of the Calaveras fault 10 km northwest of Hollister (Figure 1). An invar rod creepmeter (SHR1) was installed in the southeast shoulder of Shore Road in 1971. The rod is 6 m long, anchored at one end, and connected under tension at the other end to a sensor and dial gauge that are considered accurate to ± 0.5 mm. The rod is buried 0.5 m deep at 45° to the fault strike and monitors approximately 4 m of the total zone width (Nason and others, 1974). SHR1 records a creep rate of 9-12 mm per year (Schulz and others, 1982; Figure 2).

On April 24, 1984 at 21:15 UTC, SHR1 was the nearest creepmeter to the epicenter of the magnitude 6.2 Morgan Hill earthquake, 50 km northwest on the same fault. During the earthquake, SHR1 recorded a 0.1-mm right-lateral step, followed within 23 minutes by afterslip which totaled 12.9 mm during the next 18 hours (Figure 3a). Previously, the creepmeter had not recorded any single creep events larger than 9 mm. (The large step at the time of the Coyote Lake

1/ U.S. Geological Survey

earthquake consisted of four separate events. See Figures 2 and 3.) SHR1 lies 20 km southeast of the southern limit of the Morgan Hill earthquake rupture zone defined by the spatial extent of aftershocks (Bakun and others, 1984).

Creep also occurred at Shore Road during and after the August 6, 1979, magnitude 5.9 Coyote Lake earthquake (Figure 3c). Located 15 km southeast of that epicenter and on the same fault, Shore Road is just inside the southern boundary of the aftershock zone (Bakun and others, 1984). SHR1 recorded a 4.2-mm right-lateral coseismic step and two afterslip events in the next 24 hours, for a total of 8.3 mm (Figures 2, 3).

An unusual 3-year creep lag at Shore Road ended with the 1979 Coyote Lake earthquake (Raleigh and others, 1979; Schulz and others, 1983). A short lag may also have occurred at SHR1 prior to the Morgan Hill earthquake (Figure 2).

SURFACE DISPLACEMENT AFTER THE MORGAN HILL EARTHQUAKE

Slow but regular creep causes tension cracks to open in the fault zone across Shore Road. The current cracks have been opening since road repairs were made in 1982, and whether the afterslip on April 24 widened them is unknown. However, the day after the earthquake, fresh cracks were present in the dirt shoulders of Shore Road. The crack in the southeast shoulder near the creepmeter was 1 m long and 0.5 cm wide at its center (Figures 4, 5). Cracks in the northwest shoulder were diffuse and finer, with one extending into the pavement (Figure 6). After discovery of this surface disturbance at Shore Road, other locations of known active creep between SHR1 and Hollister were visited, and the results are reported below.

Highway 25 and McConnell Road

Approximately 5.5 km southeast of SHR1, en echelon tension cracks began forming in 1982 on the Calaveras fault trace across Highway 25 (Figure 1). The day after the Morgan Hill earthquake, Galehouse and Brown (1984) found a new line of cracks extending from the northeast edge of the pavement halfway across the highway, approximately 6.5 m west of the old line. However, these new cracks probably were not caused by the April 24 afterslip, as I found that recently planted fields beside the road were undisturbed. On McConnell Road, which crosses the fault west of Highway 25, no cracks developed in 1982 or after the April 24 earthquake (Figure 1). However, fault geometry may be complicated there (Radbruch-Hall, 1974; Slater and Burford, 1979), and movement could step to a yet unidentified trace.

Wright Road

Approximately 8.5 km southeast of SHR1, a U.S.G.S. rod creepmeter (WRT1) operating on Wright Road until 1983 recorded creep of 11-13 mm per year. An adjacent San Francisco State University survey line shows a similar rate (Jon Galehouse, oral commun., 1984). A remeasurement of the San Francisco State survey line on April 25 showed no significant change since January 1984

(Galehouse, 1984). No evidence of surface movement was visible on the fault trace in fields by Wright Road.

Hollister

Three U.S.G.S. rod creepmeters in Hollister were checked April 25 (Figure 1). Since the last dial reading on January 24, 1984, HLC1 showed 1 mm of left-lateral movement (contraction), and HLS1 and HLD1 each showed less than 1 mm of right-lateral movement (extension). At an earlier time when these stations were recording on charts, creep occurred primarily in episodes, or events, followed by months of inactivity. The largest event of the year generally occurred in summer (Schulz and others, 1982). Table 1 shows cumulative creep at the three stations as recorded from dial readings taken between April 25, 1984, and July 6, 1984. The last line on Table 1 shows the creep event amplitude range at each station since installation in April 1970. Changes between April 25 and July 6 do not appear unusual for this time of year.

Based on the Hollister creepmeter dial readings and the absence of surface fractures between Shore Road and Hollister, the large creep event recorded at Shore Road may not have extended far to the southeast. If creep did continue southeast, it may have been on a yet undiscovered trace. Cracks in soil could easily have been overlooked. There are no creepmeters on the Calaveras fault north of Shore Road. However, Galehouse and Brown (1984) found surface fractures across Highway 152, 10 km northwest of Shore Road.

DISCUSSION

Surface faulting due to unequivocal tectonic origin was not found in the vicinity of the Morgan Hill earthquake's epicenter or in the area of aftershocks (Harms and others, 1984). It is surprising, therefore, that a large slip event with associated ground fractures occurred at Shore Road 50 km southeast of the epicenter. This slip event is one of the more unusual features related to the Morgan Hill earthquake.

The segment of the Calaveras fault near Shore Road may be a zone that is unusually sensitive to changes in regional strain and stress. Such speculation is supported by the unusual three-year cessation of creep at Shore Road preceding the 1979 Coyote Lake earthquake and the possible brief lag before the Morgan Hill earthquake. Whether this segment of the fault has an unusual configuration at depth or different rock types or fault gouge is not known. The tectonic setting is unusual, being close to the Busch, Sargent, and San Andreas faults, and interaction between the faults in this area has been postulated by Mavko (1982). However, it is not clear why the fault segment near Shore Road should respond to earthquakes tens of kilometers distant.

Allen and others (1972) reported that the magnitude 6.4 Borrego Mountain earthquake of April 9, 1968, on the Coyote Creek fault in southern California triggered surface displacement on the Imperial, Superstition Hills, and San Andreas faults at distances from 45 to 70 km from the epicenter. Sieh (1982) reported similar surface displacements on the Superstition Hills and San

Andreas faults after the magnitude 6.5 Imperial Valley earthquake of October 15, 1979. These displacements on distant faults were discovered to have formed after the earthquakes and did not appear to have been caused by seismic slip. Sieh (1982) pointed out that the 1979 Imperial Valley earthquake was generated by slip along the same segment of the Imperial fault that had displayed triggered displacement after the Borrego Mountain earthquake in 1968.

Although there is no immediate explanation for Shore Road's unusual response to distant earthquakes, the site appears to be unusually sensitive to changes in regional strain or stress.

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TABLE 1

Amount of Right-Lateral Creep (mm) Accumulated Since April 1970
at Sites in Hollister

Date of Dial Reading	HLC1	HLS1	HLD1[1]
April 25, 1984	132.05	95.72	25.58
May 4, 1984	134.07	99.50	27.10
June 6, 1984	134.27	100.54	not read
July 6, 1984	140.28	103.68	27.15
Range of creep event amplitude, mm	-0.23[2] to 9.5	0.1 to 9.2	0.2 to 5.0

[1] HLD1 crosses only a small portion of one end of the creeping trace.
[2] Minus sign indicates left-lateral movement.

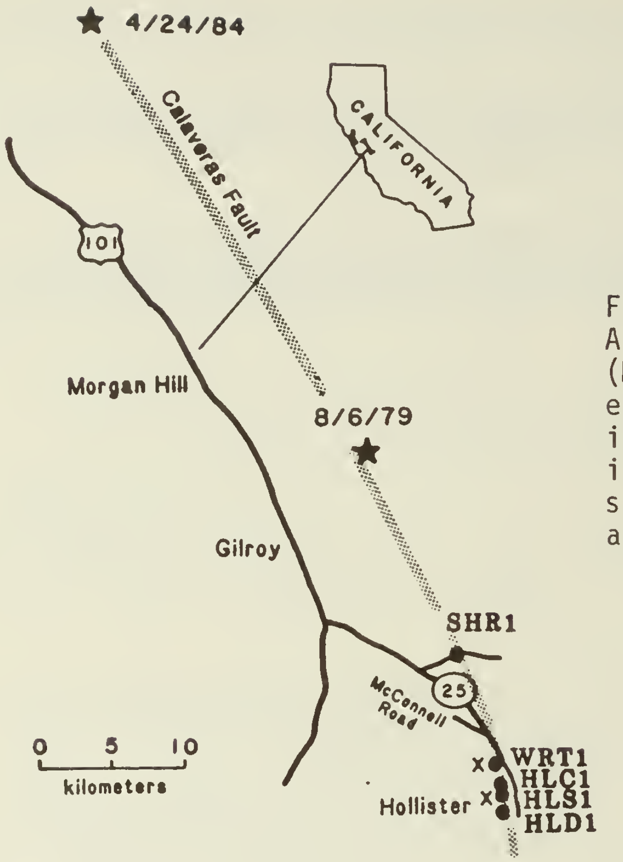

Figure 1. Map showing epicenters of April 24, 1984, Morgan Hill earthquake (M_L = 6.2) and August 6, 1979, Coyote Lake earthquake (M_L = 5.8) (stars). Large dots indicate U.S.G.S. creepmeters and X's indicate San Francisco State University survey lines. Stippled line indicates approximate trace of Calaveras fault.

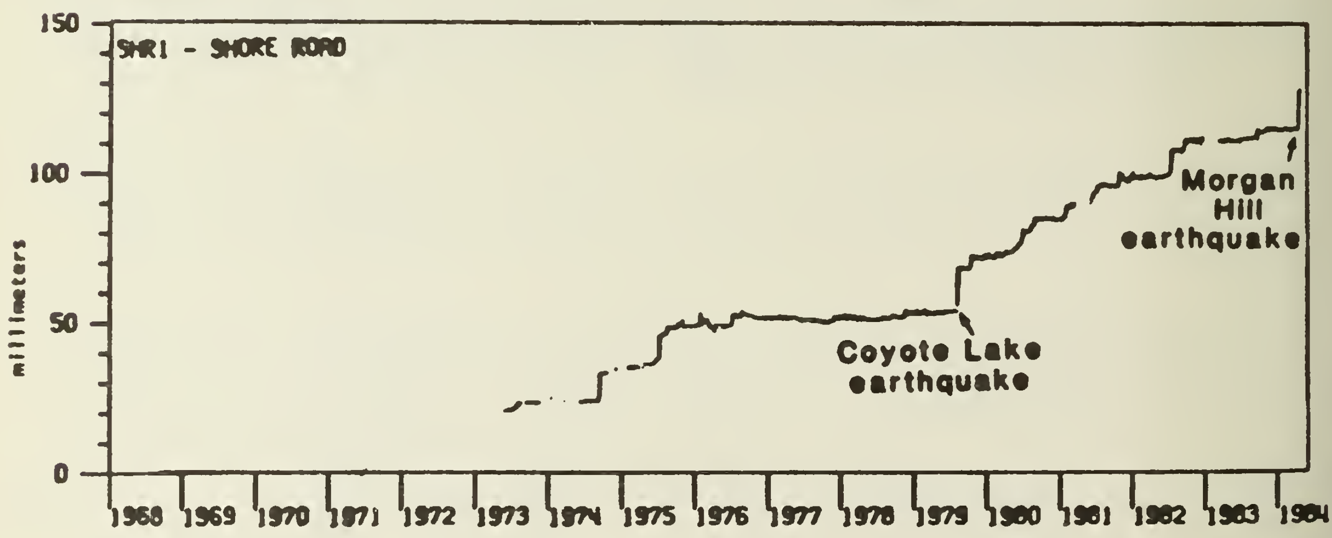

Figure 2. Long-term creep at SHR1 (Shore Road). Note 3-year creep lag preceding August 6, 1979, Coyote Lake earthquake 15 km distant. There may have been a brief lag preceding the Morgan Hill earthquake, 50 km distant. The step at the time of the Coyote Lake earthquake consists of four separate events, a coseismic step of 4.2 mm, two creep events after the earthquake of 1.9 and 2.2 mm, respectively, and a 4.9 mm creep event on August 11, 5 days after the earthquake.

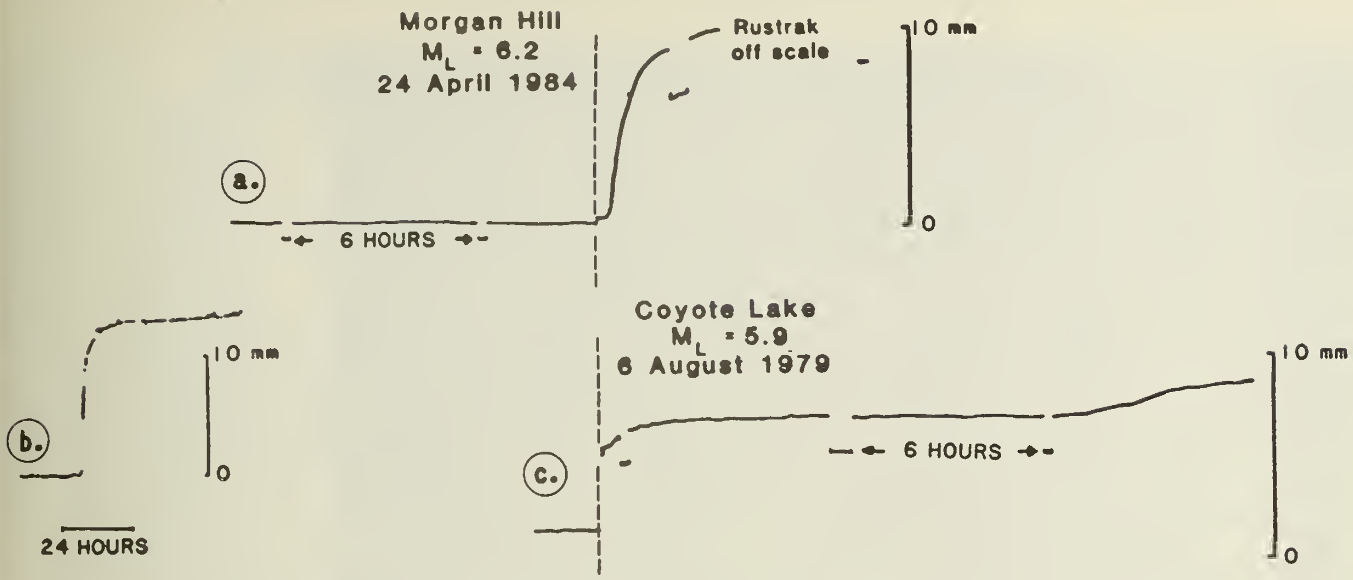

Figure 3. (a) Rustrak trace showing SHR1's response to April 24, 1984, Morgan Hill earthquake. A 0.11-mm coseismic step was followed within 23 minutes by 12.9 mm of afterslip over the next 18 hours. Recorder went off scale after 4 hours. (b) Telemetry trace showing entire event (ten-minute samples). (c) Rustrak trace showing SHR1's response to August 6, 1979, Coyote Lake earthquake. A 4.2-mm coseismic step was followed by 4.1 mm afterslip in two events over the next 24 hours.

Figure 4. View northeast along trace of Calaveras fault at Shore Road 10 km northeast of Hollister. SHR1 lies in road shoulder off right side of photograph and crosses the trace at an angle of 45°. Cracks in road began after repaving in 1982. White, 15-cm scale in lower right-hand corner indicates location of fresh crack in road shoulder apparently caused by afterslip following the April 24 earthquake (see Figure 5).

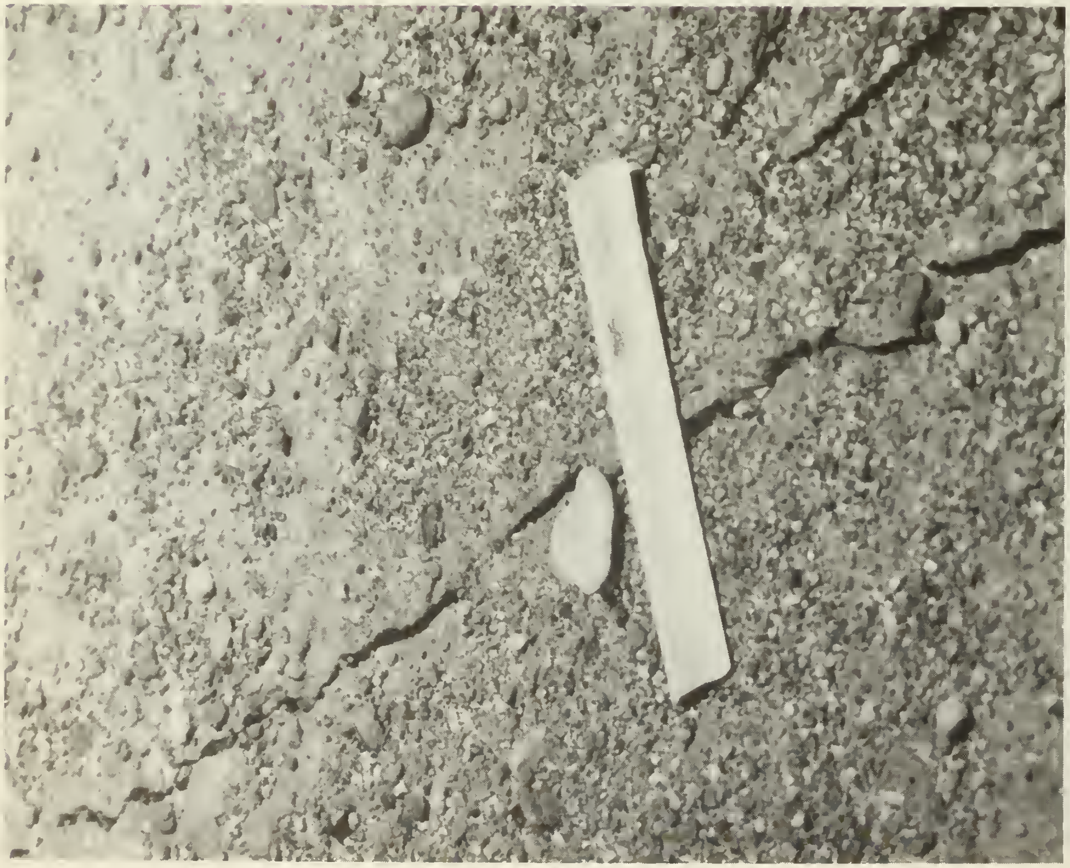

Figure 5. Close-up of fresh crack 1 m long and 0.5 cm at widest opening beside Shore Road. Scale is 15 cm long.

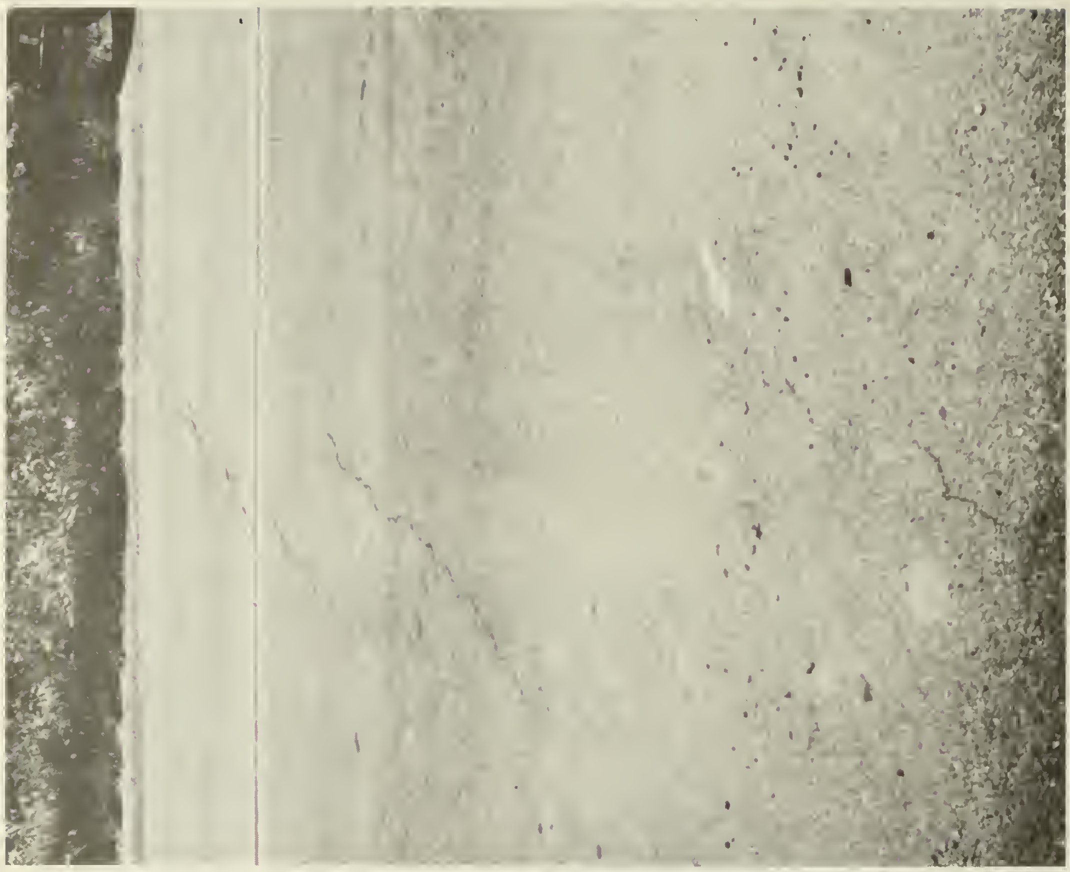

Figure 6. View southeast along Calaveras fault trace at Shore Road. SHR1 is in shoulder in left upper center of picture. Arrow indicates hairline crack extending from dirt shoulder into roadway.

NEAR-SURFACE GEOLOGY AND SEISMIC WAVE VELOCITIES AT SIX STRONG-MOTION STATIONS NEAR GILROY, CALIFORNIA*

by

Thomas E. Fumal, James F. Gibbs, and Edward F. Roth [1/]

ABSTRACT

Geologic and P- and S-wave velocity logs are presented from boreholes 20-60 m deep at five stations of the Gilroy strong-motion array and at the Coyote Lake Dam, South Abutment station (originally called San Martin-Coyote Creek when first installed by USGS). The geology at the Coyote Dam site is very complex. The instrument pad is located on or partially on a prominent mass of silica-carbonate rock and serpentine imbedded in sheared rock of the Franciscan assemblage. Our borehole, 70 m to the southwest, penetrated only sedimentary rocks and is separated from the instrument site by a strand of the Calaveras fault zone. In view of this, the relatively low shear wave velocities measured in the USGS borehole (250-480 m/s) should not be used to characterize this site; further investigations will be necessary to determine the velocity structure underlying the strong-motion instrument at Coyote Lake Dam.

INTRODUCTION

Significant records have been obtained at five stations of the Gilroy strong-motion array within 16 km of the Coyote Lake earthquake (August 6, 1979, $M_L = 5.9$) and within 40 km of the Morgan Hill earthquake (April 24, 1984, $M_L = 6.1$). This array was installed by the U.S. Geological Survey in 1971 and presently is operated jointly with the California Division of Mines and Geology. Records from this array are particularly useful for investigating the effects of site conditions on strong ground motion, as the subsurface geology changes dramatically over a short distance. The array (fig. 1) extends from sandstone in the Franciscan assemblage on the southwest across alluvium of the Santa Clara Valley to Tertiary sandstone on the northeast 10 km away. Interpretation of the strong-motion data from these stations requires information about the geologic materials underlying each site including shear-wave velocities. Following the Coyote Lake earthquake, the U.S. Geological Survey (USGS) began studying the near-surface geology and the compressional- and shear-wave velocity structure at five of the Gilroy array stations and at the nearby Coyote Lake Dam station. The results of these investigations have been reported in detail in Fumal and others (1982) and are summarized in this report.

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1/ U.S. Geological Survey

DATA ACQUISITION AND PROCESSING

At each strong-motion station rotary-wash equipment was used to drill a borehole 20-30 m deep at sites on bedrock and 30-60 m deep at sites on alluvium. An additional hole was drilled at Mission Trails Motel (station 2) in order to find the depth to bedrock (180.5 m to Franciscan sandstone). The geologic and seismic velocity logs from this deep borehole are presented in Joyner and others (1981).

Samples of each dominant type of material encountered were recovered during drilling. Two to four samples were taken at each of four sites (stations 2, 3, 4, and Coyote Lake Dam); no samples were recovered at two of the bedrock sites--Gavilan water tank and Cañada Road--San Ysidro (stations 1 and 6). A geologic log including soil texture and color and estimates of hardness and fracture spacing in rocks was compiled for each hole from descriptions of the samples and a field log made at the time of drilling. The field log was based on continuous monitoring of the drill cuttings and roughness and rate of drilling, on-site inspection of samples and inspection of nearby outcrops. Simplified versions of the geologic logs are presented in figures 2-7.

Shear waves were generated at the ground surface using a horizontal traction source similar to the one discussed by Warrick (1974). Compressional waves were generated by using both a vertical hammer blow on a striker plate and a blasting cap. Recordings of the seismic signals were made in the boreholes with a three-component geophone package usually at depth intervals of 2.5 m. P- and S-wave velocities were calculated from the measured travel times for depth intervals determined from changes in slope of travel-time curves. In order to minimize the effect of picking errors, these depth intervals are a minimum of 5 m (three travel-time measurements) for materials with shear-wave velocities less than 350 m/s and 7.5 m (four travel-time measurements) for stiffer materials. The travel-time curves and calculated P- and S-wave interval velocities are shown in figures 2-7.

RESULTS

The near-surface geology and shear wave velocities at each strong-motion station can be summarized as follows:

Gavilan water tank (station 1)--Sandstone in the Franciscan assemblage (Dibblee, 1973a) with minor shale, hard, fracture spacing mostly very close to close in moderately weathered rock to 10-m depth (V_S = 780 m/s) and close to wide in fresh rock (V_S = 2230 m/s).

Mission Trails Motel (station 2)--Alluvial fan deposits of Holocene age (Helley and Brabb, 1971) to 8-m depth (V_S = 275 m/s) over Pleistocene alluvium to 180.5-m depth (V_S = 300-460 m/s to 40 m depth, about 630 m/s from 40- to 180-m depth).

Gilroy sewage treatment plant (station 3)--Interfluvial basin deposits of Holocene age (Helley and Brabb, 1971) to 6-m depth (V_S = 165 m/s) over Pleistocene alluvium to greater than 60-m depth (V_S = 255-625 m/s).

San Ysidro School (station 4)--Fluvial deposits of Holocene age (Helley and Brabb, 1971) to 9-m depth (V_s = 145 m/s) over mostly fine-grained Pleistocene alluvium to greater than 30-m depth (V_s = 285 m/s).

Cañada Road-San Ysidro (station 6)--Unnamed marine sedimentary rocks of early Eocene-Paleocene and (or) Late Cretaceous age (Dibblee, 1973b); deeply to moderately weathered sandstone with very close to close fracture spacing to 18-m depth (V_s = 625 m/s) over fresh, hard shale with mostly close to moderate fracture spacing and some sheared zones (V_s = 690 m/s).

Coyote Lake Dam (CYC)--The geology at this site, located within the Calaveras fault zone, is very complex. The strong-motion instrument is situated at the left (southwest) abutment of the dam next to a prominent outcrop of silica-carbonate rock and serpentine. The concrete base for the instrument may rest on as much as 1.5 m of fill on the edge of a steep south-facing slope partially buried by the embankment of the dam (Tepel, 1984). The USGS drill hole was located about 70 m to the southwest of the accelerograph shelter in an area mapped as serpentine by Dibblee (1973a). Drilling, however, revealed about 2.5 m of fill over a sequence of soft to firm mudstone and sandstone (V_s = 250-480 m/s). A report prepared by Galloway and others (1935) describing tunnels cut prior to dam construction indicates that these sedimentary rocks are in fault contact with serpentine that is in turn separated from the main serpentine mass by a zone of highly sheared rock about 5 m thick. The sedimentary rocks are apparently part of a block of Plio-Pleistocene rocks within the Calaveras fault zone. This block is cut by several minor faults and includes a zone of volcanic breccia in fault contact with the sedimentary rocks. The serpentine knob on which the strong-motion instrument is located is part of a disturbed zone developed in shale and sandstone of the Franciscan assemblage extending beneath most of the valley floor. Several wide zones of highly sheared rock are present, increasing in abundance toward the left abutment. The disturbed zone crops out downstream from the serpentine knob and consists of large (up to 10 m in diameter) blocks of serpentine, sandstone, and shale in a matrix of highly sheared serpentine and shale.

Considering the geology in the vicinity of the Coyote Lake Dam strong-motion instrument, the relatively low shear-wave velocities measured in the USGS borehole (250-480 m/s) should not be used to characterize the materials underlying the instrument pad. Shear-wave velocites of 600-800 m/s have been recorded in serpentine and sheared rock at several other sites investigated by the USGS elsewhere in northern California. Future investigations will be necessary in order to characterize with certainty the velocity structure underlying the instrument at this site.

ACKNOWLEDGEMENTS

The authors wish to thank all of the property owners who allowed access for drilling and making the velocity measurements. Dick Warrick and Ron Porcella of the USGS helped with the seismic measurements at the Coyote Lake Dam station and provided very helpful review comments.

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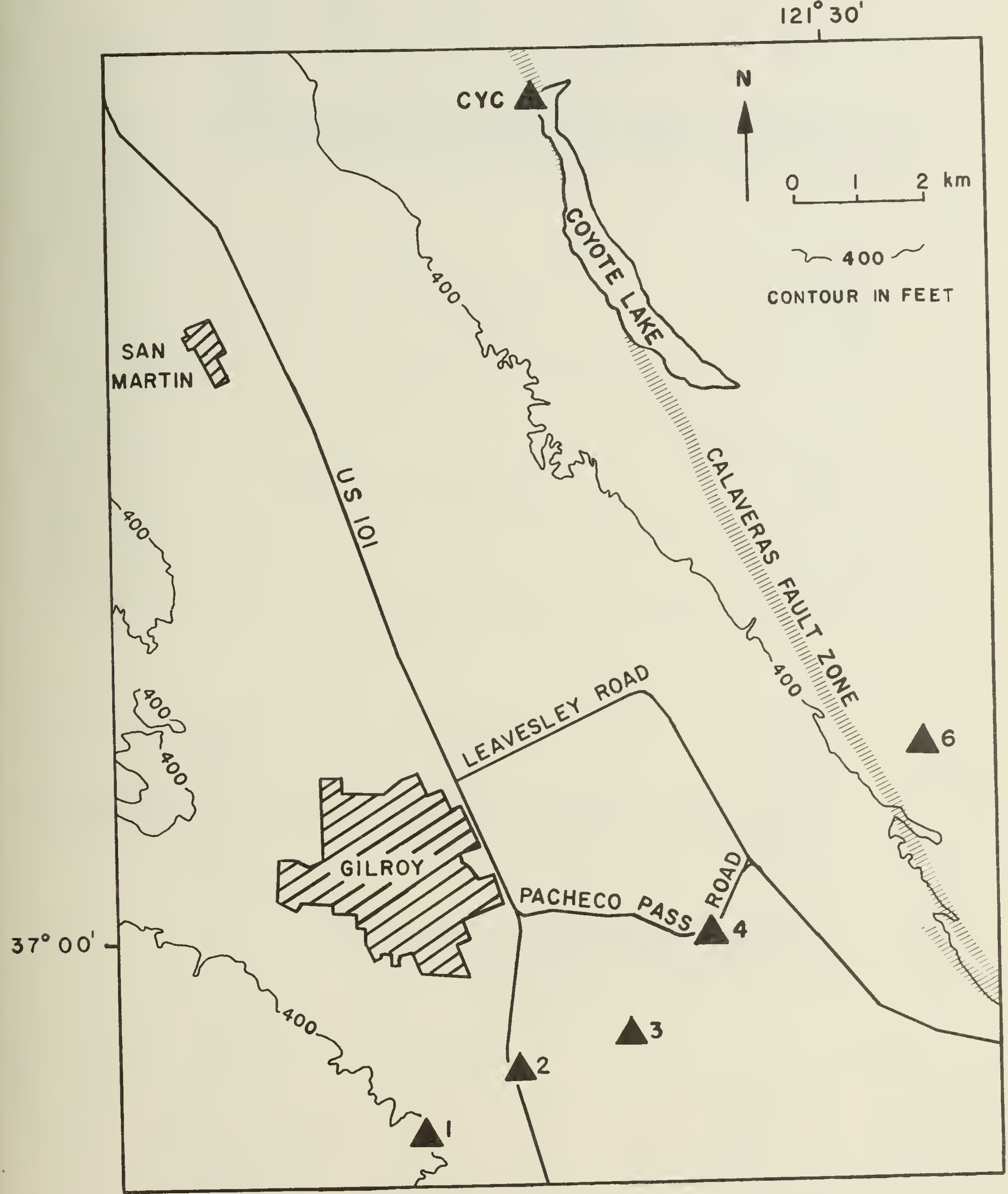

Figure 1. Location of strong-motion stations where downhole seismic velocity measurements were made. Stations as follows: 1, Gavilan water tank; 2, Mission Trails Motel; 3, Gilroy Sewage Treatment Plant; 4, San Ysidro School; 6, Cañada Road - San Ysidro; CYC, Coyote Lake Dam.

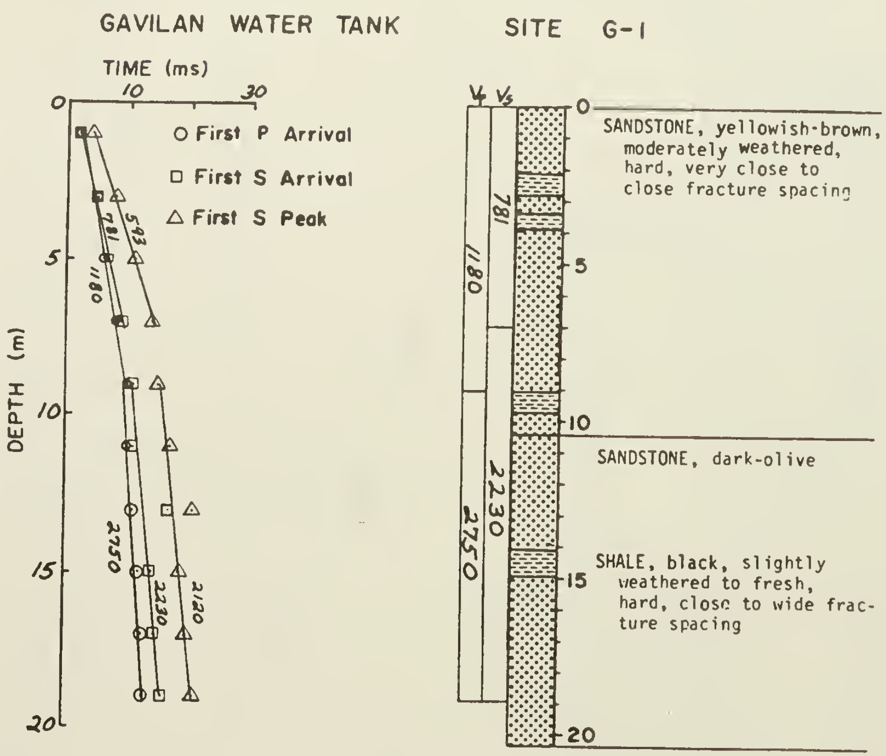

Figure 2. Travel-time curve, calculated P- and S-wave velocities, and simplified geologic log at Gavilan water tank. Calculated velocities are in meters per second.

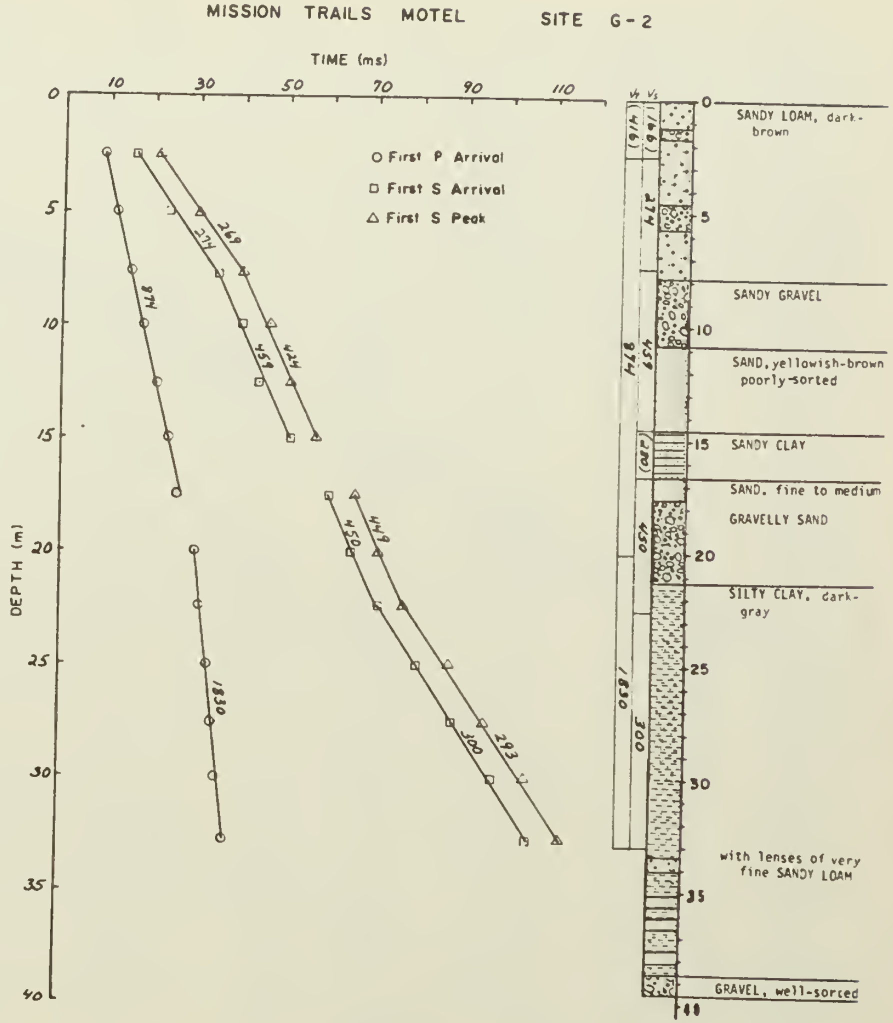

Figure 3. Travel-time curve, calculated P- and S-wave velocities, and simplified geologic log at Mission Trails Motel. Calculated velocities are meters per second. Values in parentheses are not well-determined.

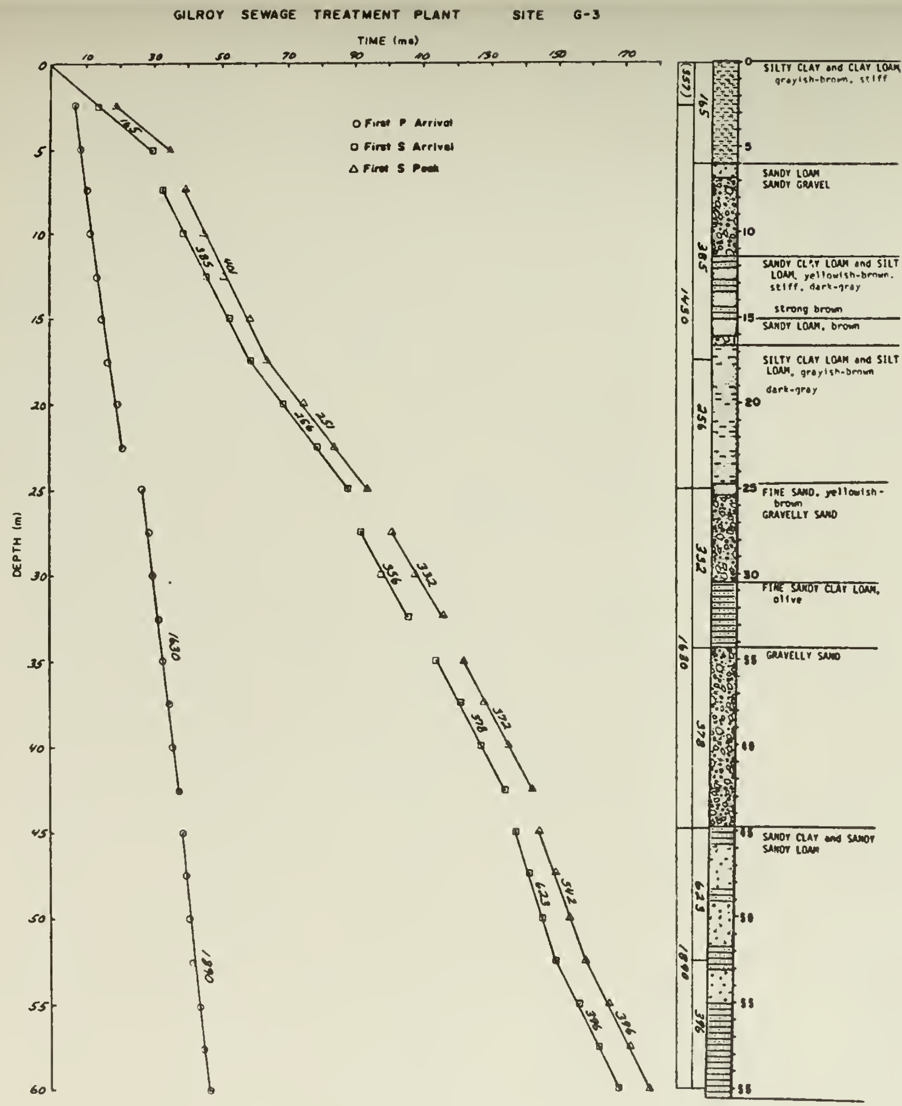

Figure 4. Travel-time curve, calculated P- and S-wave velocities, and simplified geologic log at Gilroy Sewage Treatment Plant. Calculated velocities in meters per second. Value in parentheses is not well-determined.

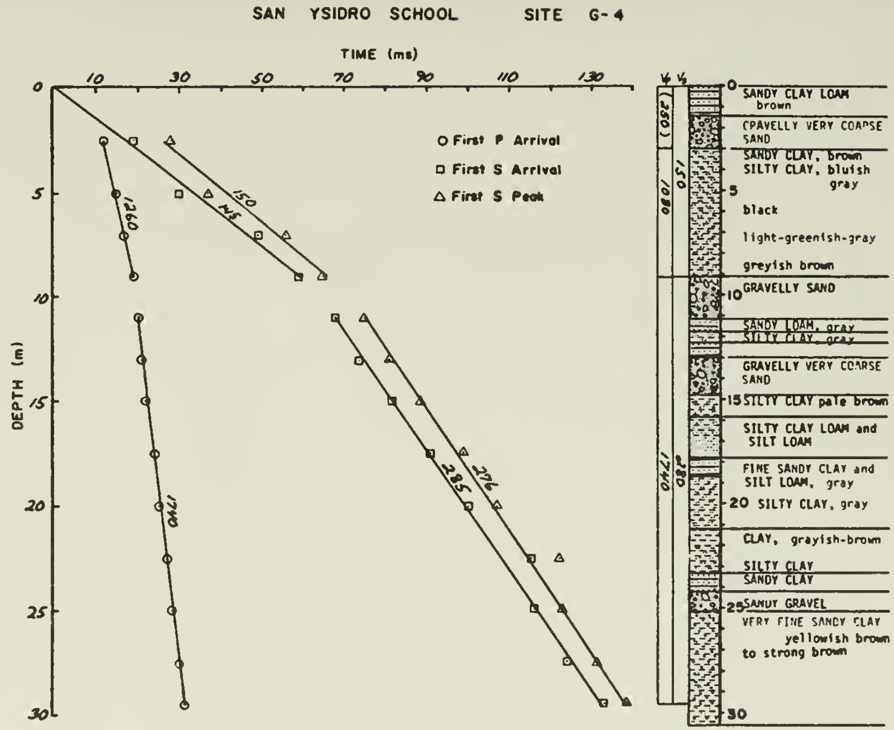

Figure 5. Travel-time curve, calculated P- and S-wave velocities, and simplified geologic log at San Ysidro School. Calculated velocities are in meters per second. Value in parentheses is well-determined.

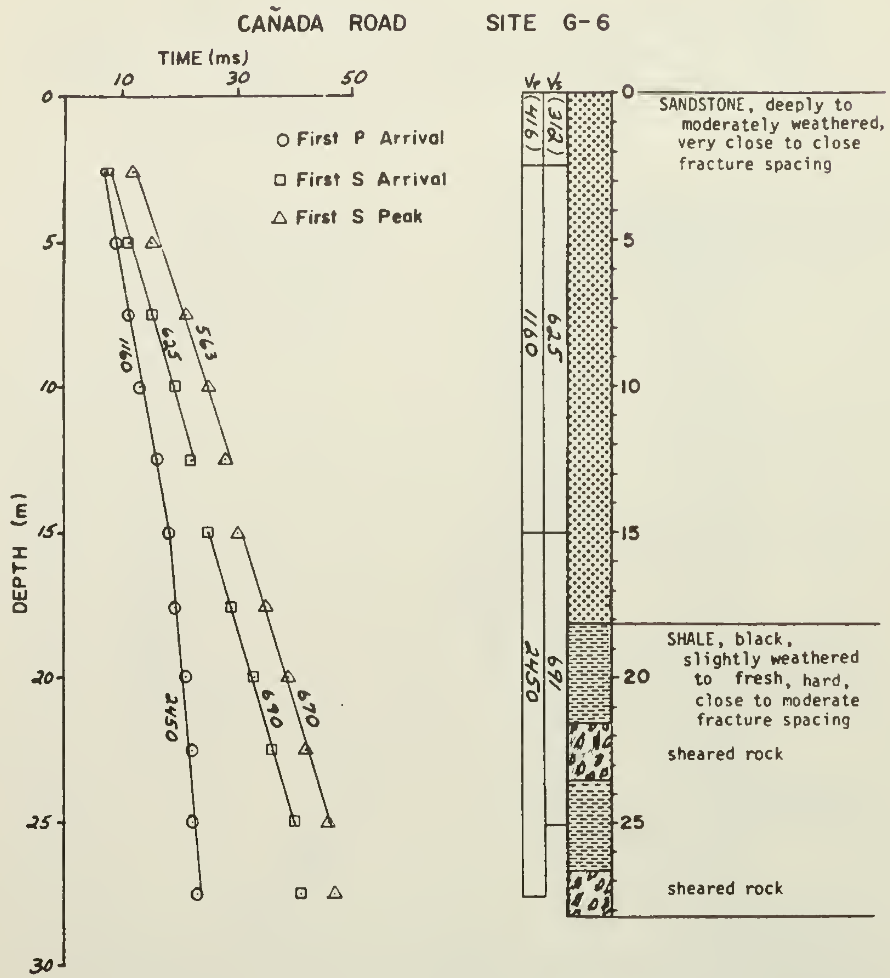

Figure 6. Travel-time curve, calculated P- and S-wave velocities, and simplified geologic log at Canada Road - San Ysidro. Calculated velocities are in meters per second. Values in parentheses are not well-determined.

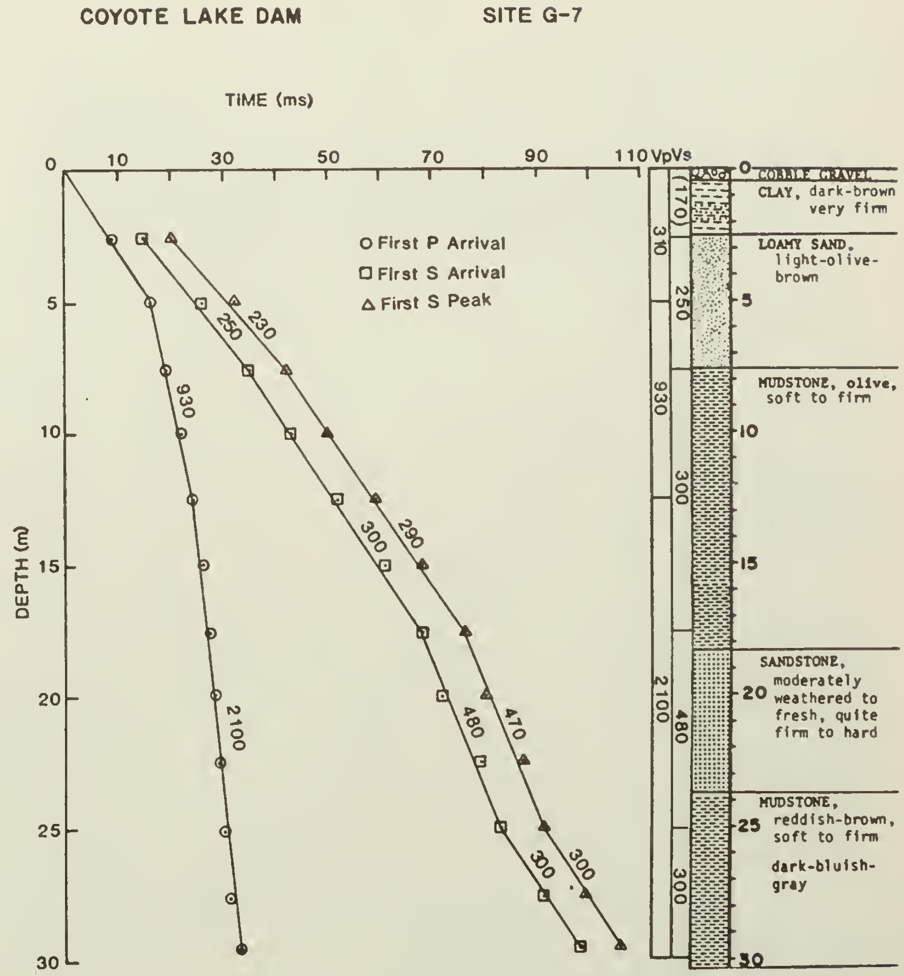

Figure 7. Travel-time curve, calculated P- and S-wave velocities, and simplified geologic log at Coyote Lake Dam. Calculated velocities are in meters per second. Value in parentheses is not well-determined.

Section IV

SEISMOLOGICAL INVESTIGATIONS

THE 1984 HALLS VALLEY ("MORGAN HILL") EARTHQUAKE SEQUENCE: APRIL 24 THROUGH JUNE 30

by

Robert A. Uhrhammer[1] and Robert B. Darragh[2]

ABSTRACT

On April 24, 1984 at 21:15 UTC, a large earthquake occurred on the Calaveras Fault in the vicinity of Halls Valley, California (epicenter 37°19.2'N, 121°41.9'W). The earthquake had a mean local magnitude of 6.2 and a maximum Modified Mercalli Intensity of VIII. By June 30, 1984, an aftershock sequence of 33 earthquakes magnitude 3.0 or larger had occurred in the region. The largest aftershock of M_L 4.5 occurred nine days after the mainshock on May 3, 1984 at 13:07 UTC. A cumulative plot gives a b-value of 0.82 ± 0.099 for the interval of April 24 to June 30, 1984. This sequence follows Omori's relation with index 0.74.

The rate of seismicity from historical catalogs, compiled at the U. C. Seismographic Stations yielded an average recurrence time of 160 ± 60 years for an $M_L \geqslant 6.2$ event occurring in a 30 km segment of the Calaveras Fault. Other evidence from the repeat times of earthquakes with local magnitude near 6.0 suggest a recurrence period of 75 years. These estimates are in reasonable agreement.

A moment of 1.1×10^{25} dyne-cm for the mainshock was estimated from broadband displacement seismograms recorded at Berkeley ($\Delta \approx 79$ km). The moment and the rupture area inferred from the aftershocks suggest a mean fault displacement of 30 cm. Seismic moments of all earthquakes with $M_L \geqslant 3.0$ were estimated from Wood-Anderson seismograms recorded at either Berkeley or Mt. Hamilton. The moment for the mainshock computed from the Wood-Anderson records agrees well with the seismic moment from the broadband displacement seismograms.

The Halls Valley sequence and the Coyote Lake (1979) sequence are adjacent to each other on the Calaveras Fault. These sequences have many similarities in their temporal and spatial characteristics. Important seismograms of the mainshocks at Berkeley and at the Richmond Field Station are compared and discussed. The most striking difference between the mainshocks is the relative complexity of the Halls Valley mainshock seismograms recorded at Berkeley.

INTRODUCTION

A damaging earthquake of local magnitude 6.2 occurred on April 24, 1984 (1:15 p.m. PST) on the Calaveras fault (see Figures 1 and 5) approximately 16 kilometers east of San Jose in Halls Valley. The earthquake was felt strongly throughout the San Francisco Bay Area and vicinity. A maximum intensity of MM VIII is assigned based on the observation that a few houses in the Morgan Hill suburb of Jackson Oaks located at the southern end of Anderson Lake shifted from their foundations. In this paper the earthquake is referred to as the "Halls Valley" earthquake rather than the "Morgan Hill" earthquake in accord with the tradition of naming the earthquake after the geographical location of the epicenter.

The largest aftershock, M_L 4.5, occurred 9 days after the mainshock beneath the San Felipe Valley. Fifteen aftershocks with $M_L \geqslant 2.5$ and three aftershocks with $M_L \geqslant 3.5$ occurred in the first 24

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hours of the sequence (see Table 1). Ten aftershocks, $M_L \geqslant 3.5$, occurred in the 6 week period following the mainshock.

This report summarizes observations largely from the University of California, Berkeley (UCB) seismographic network and focuses on the following general seismological aspects: analysis of the historical seismicity along the Calaveras Fault, estimation of local magnitude , estimation of seismic moment, a statistical analysis of the sequence and a comparison of the Halls Valley earthquake sequence with the Coyote Lake earthquake sequence of 1979.

HISTORICAL SEISMICITY

The M_L 6.2 Halls Valley earthquake is the fourth earthquake sequence of $M_L \geqslant 6$ to have occurred along a 200 km segment of the Central Coast Ranges, between Monterey and Santa Rosa, during this century. The seven largest earthquakes ($M_L \geqslant 6.0$) that have occurred in the region since 1897 are listed in Table 2. The Halls Valley mainshock is probably a repeat of the 1911 Coyote mainshock (Bufe et al., 1979; Bakun et al., 1984) and the 1979 Coyote Lake mainshock (see Table 6) is similar in many aspects to the 1897 Coyote Lake event (Reasenberg and Ellsworth, 1982) suggesting a recurrence period of approximately 75 years. The long-term slip-rate is approximately 1.5 cm/year with 1.2 cm/year of observed surface creep along the Calaveras Fault (Herd, 1979; Ellsworth et al., 1981) implying that at least 0.3 cm/year of slip accumulates on the average. If we assume that the Halls Valley mainshock is predictable in both time and size with a 75 year recurrence period then 23 cm of slip was accumulated before the Halls Valley mainshock. The calculated average fault slip in the mainshock was 20-40 cm with larger values preferred (see next section and Bakun, et al., 1984). Two possible explanations for the difference between the slip accumulation and dissipation are that the rate of slip is not stationary in time and that the rate of creep decreases with depth through the seismogenic zone.

Epicenters of earthquakes with $M_L \geqslant 2.5$ (Bolt and Miller, 1975 and subsequent Bulletins of the U.C. Berkeley Seismographic Stations) that occurred within a 8,500 km^2 area, (50 km wide by 170 km long) centered on the Calaveras Fault, during the 40 year interval from 1943 to 1982, are shown in Figure 1. From 1943 to 1982, 1032 earthquake sequences with mainshock $M_L \geqslant 2.5$ occurred in the region and the inferred rate of seismicity for $M_L \geqslant 2.5$ is $r=3.0 \pm 0.3$ sequences per year per 1000 km^2 . A sequence is defined as one or more earthquakes that occur within a relatively small time and distance window centered on the time and location of the first earthquake. For estimating the rate of sequence occurrence a 14 day time and 30 km distance window is adequate. If only the earthquakes occurring within 6 km of the trace of the Calaveras Fault are considered, the rate of seismicity for $M_L \geqslant 2.5$ is $r = 4.0 \pm 0.3$ sequences per year per 100 km long fault segment. The cumulative rate of seismicity is:

$$\log N = 3.40 - 0.77\, M_L \tag{1}$$

and the associated variance is

$$\sigma^2_{\log N} = 0.00879 - 0.00444\, M_L + 0.000610 M_L^2, \tag{2}$$

where: N is the cumulative number of earthquake sequences with a magnitude of M_L or larger that has been normalized to sequences per year per 1000 km^2. The coefficients in (1) and (2) are estimated by a maximum likelihood procedure (Aki, 1965).

In the approximately 30 km segment of the Calaveras Fault that ruptured in the Halls Valley mainshock from 37°06'N to 37°20'N latitude, 87 earthquake sequences with mainshock $M_L \geqslant 2.8$ have occurred in the 40 year interval 1943-1982. The cumulative rate of seismicity is

$$\log N = 2.64 - 0.78\, M_L \tag{3}$$

and the associated variance is

$$\sigma^2_{logN} = 0.246 - 0.0792\ M_L + 0.00706 M_L^2. \tag{4}$$

The calculated interoccurrence time (T) for a $M_L \geqslant 6.2$ earthquake along this segment of the Calaveras Fault is T = 160±60 years.

A space-time plot of the historical seismicity with $M_L \geqslant 2.5$ along the Calaveras Fault is shown in Figure 2. Of particular interest is the uniform background seismicity in the region between Mt. Hamilton and Coyote Lake from 1943 to 1982. For this sample there is no apparent "seismic gap" in the historical seismicity in the Halls Valley aftershock zone. The relatively low level of seismicity 30 to 70 km to the north of Mt. Hamilton in Figure 2 suggests that strain energy release is lower in this section of the Hayward fault system. This zone may be a remnant of the major October 11, 1868 Haywards earthquake that ruptured a 45 km segment of the Hayward Fault between BKS and MHC on Figure 1. Another possible explanation is that strain energy release is distributed over a broader area due to the bifurcation of the Hayward and the Calaveras faults (see Figure 1).

From 1971 to 1982, 33 earthquakes with $M_L \geqslant 2.5$ and unrestrained focal depths occurred along the 37°12'N to 37°24'N latitude segment of the Calaveras Fault zone centered around the epicenter of the Halls Valley mainshock. The mean depth of the 33 hypocenters is 6.4±1.92 km with a mode of 8 km. The mainshock of the Halls Valley sequence occurred at a depth of 8.4±0.14 km which is consistent with Sibson's (1982) model that large ruptures with $M_L > 5.5$ nucleate at the base of the seismogenic zone defined by the background seismicity.

CHARACTERISTICS OF THE MAINSHOCK

The mainshock occurred at 21:15 UTC on April 24, 1984. The adopted UCB hypocentral location is given in Table 1. This location is based on the P-wave onset times and the station adjustments at 8 stations in the permanent UCB network shown in Table 3. A linear velocity gradient over a half-space model with the depth to half-space of 25 km was used to locate the earthquakes in the sequence. The P-wave velocity ranges from 5.28 km/sec at the surface to 7.16 km/sec above the half-space and 7.70 km/sec in the half-space. P-wave polarities at UCB stations (see Table 3) are consistent with a right-lateral strike slip mechanism in the mainshock.

A local magnitude of 6.17±0.20 based on six observations for the mainshock was determined from the maximum trace amplitudes measured on the 100X torsion seismograms shown in Figure 3 recorded at Berkeley (BRK) and from the standard Wood-Anderson torsion seismographs at Mineral (MIN) and at Arcata (ARC) (see Table 4). The Pasadena (California Institute of Technology) local magnitude estimate of 6.34±0.18 based on 5 observations (Dr. L. K. Hutton, personal communication, (M_L) 1984) is approximately 0.2 magnitude units higher than the Berkeley estimate. The combined M_L based on 11 observations is 6.2±0.20 as shown in Table 4. Eaton(1984) reports a similar observation from low gain horizontal and vertical CALNET seismometers. An average magnitude of 6.2 based on three observations is given for northern California and an average magnitude based on ten observations of 6.5 to 6.7 is given for southern California. The systematic difference in the M_L estimates from northern and southern California stations may be attributed to a combination of source effects and propagation path effects. One possibility is that the attenuation curve (-logA_o, Richter, 1935) for estimating M_L may be biased for propagation paths outside of southern California resulting in systematic differences in M_L estimates from northern and southern Californian stations. In order for the southern Californian stations to give systematically higher M_L estimates, the wave attenuation must be higher in northern California than in southern California. A second possibility is due to the effect of a propagating rupture that smooths the high frequencies by destructive interference between waves emitted from different parts of the rupture surface. The smoothing is most severe in the direction opposite to the rupture propagation (p. 810, Aki and Richards, 1980). As an example, if the high frequency smoothing caused by the moving rupture reduces the maximum trace amplitude by 30 percent, the effect is to reduce the M_L estimate by approximately 0.15. The distribution of the aftershocks to the southeast of

the mainshock epicenter (Figure 5) implies that the rupture propagated unilaterally towards the southeast. The Berkeley M_L estimate then may be biased low with respect to the Pasadena M_L estimate because the Berkeley stations are within 30° of the back azimuth of the rupture direction (Table 4) and the Pasadena stations are within 40° of the forward azimuth of the rupture direction. The peak accelerations from the strong-motion data for the Halls Valley mainshock (Brady et al., 1984) also exhibit a strong directional character. The observed peak accelerations in the rupture direction are approximately 3 times higher than the observed peak accelerations in the back azimuth direction at comparable distances. The strong-motion data is compatible with the effect of a propagating rupture. Thus, rupture propagation towards the southeast is considered to be the dominant cause of the systematically higher M_L values observed in southern California.

The seismic moment of the mainshock was estimated from the three-component ultra-long-period (ULP) displacement seismograms recorded at Berkeley (BKS:$\Delta \approx 79$ km; Az$\approx$320). The ULP displacement seismograms are shown in bottom of Figure 4. The relative complexity of the Halls Valley waveforms compared to the Coyote Lake waveforms implies that the source can not be explained in terms of a simple uniform rupture process. On the vertical component, approximately 95 percent of the source energy is recorded from 7 to 12 seconds after the initial P-wave onset at point P1 on Figure 4. In Figure 4 this energy begins with the large compressional arrival on the vertical component (at point P2) at 7 seconds after P and ends approximately 5 seconds later with the S-wave arrival on the NE component. The asymptotic DC spectral level of the SH-wave displacement pulse, recorded on the transverse (NE) component of the ULP, is $\Omega_0(\mathrm{SH}) = 0.9$ cm-sec. Thus the seismic moment is 1.1×10^{25} dyne-cm, assuming that the effects of the free surface and of the source radiation pattern average out to unity. The moment estimated from standard Wood-Anderson seismograms (Bolt and Herraiz, 1983) listed in Table 1 agrees with the broadband moment estimate for the mainshock.

The inferred fault dimensions for the mainshock are about 6 km in width by 16 km (distance from the epicenter to the later source) to 26 km (distance from the epicenter to the southern extent of the aftershock sequence shown in Figure 5 and discussed in the next section). From the seismic moment and these dimensions, we infer an average fault slip of about 20 to 40 cm in the mainshock.

SEQUENCE CHARACTERISTICS

An inspection of the standard Wood-Anderson and vertical Benioff seismographs at Mt. Hamilton for the week prior to the mainshock located two earthquakes with $M_L \geqslant 1.0$ that occurred within approximately 5 km of the Halls Valley mainshock hypocenter. These earthquakes occurred on April 21 at 13:37 UTC ($M_L = 1.5$) and on April 24 at 03:41 UTC ($M_L = 1.1$). For comparison, the rate of background seismicity from (3) in the 30 km segment of the Calaveras Fault spanning the epicenter is 72 ± 29 earthquakes per year with $M_L \geqslant 1.0$. On the assumption that the earthquakes follow a Poisson distribution, the probability of two earthquakes with $M_L \geqslant 1.0$ occurring in the week prior to the mainshock is 24 percent.

From April 24, 1984 to June 30, 1984, 69 earthquakes ($2.5 \leqslant M_L \leqslant 6.2$) occurred in the 1984 Halls Valley earthquake sequence (see Table 1 and Figure 5). The local magnitude estimates listed in Table 1 are from the maximum trace amplitudes measured on the standard Wood-Anderson torsion seismograms at Mt. Hamilton (MHC:$\Delta \approx 5$ to 30 km), Berkeley (BKS:$\Delta \approx 75$ to 105 km), and for the larger events, Mineral (MIN:$\Delta \approx 340$ km) and Arcata (ARC:$\Delta \approx 450$ km). The threshold magnitude of 2.5 corresponds to a maximum trace amplitude of 4.0 mm at MHC and 0.3 mm at BKS for an earthquake near the southern end of Anderson Lake.

The local magnitude distribution of aftershocks (see Figure 6) may be represented fairly closely by the Gutenberg-Richter formula

$$\log N(M_L) = a - bM_L \tag{5}$$

where N is the cumulative number of earthquakes with local magnitude greater than or equal to M_L. A maximum likelihood estimate of the parameters in (5) (Aki, 1965) yields: $a=3.96\pm0.30$ and $b=0.815\pm0.099$. A b-value of 0.82 ± 0.10 is typical for earthquake sequences that have occurred in the California Coast Ranges (Shi and Bolt, 1982). The probability distribution that the difference d in M_L, between the mainshock and the largest aftershock, is greater than or equal to D is given by (Utsu, 1969)

$$P(d \geqslant D) = b \; ln 10 \times 10^{-bD} \tag{6}$$

where: b is the b-value from (5). The largest aftershock in the Halls Valley sequence is 1.7 M_L units smaller than the mainshock. The probability from (6) of this occurring by chance alone is less than 8 percent. For comparison, Table 5 lists the difference d in M_L for some of the strike-slip earthquake sequences that have occurred near California. The d values are all greater than 1.2 M_L units and the probability of this occurring by chance alone ranges from less than one percent to approximately 20 percent from (6). One inference is that the mainshock of a large strike-slip California earthquake sequence does not follow the same distribution as their aftershock sequence. One possibility is that large strike-slip mainshocks, that occur in California, tend to reduce the accumulated strain energy to a relatively uniform low level over the entire length of the rupture surface. Then the occurrence of regions on the rupture surface with sufficient residual strain energy and cross-sectional area to produce large aftershocks with $d<1$ would be unlikely.

The observed variation in the hourly frequency of aftershocks (see Figure 7) follows the classic Type 1-A mainshock-aftershock sequence distribution (Mogi, 1963). Assuming that the aftershocks are distributed according to a non-stationary Poisson process, the intensity function $n(t)$ is given by the modified Omori's formula

$$n(t) = Kt^{-p}, \tag{7}$$

where K depends on the lower magnitude bound (M_L=2.5) of earthquakes counted in $n(t)$ and p is independent of the lower magnitude bound (Utsu, 1969; Utsu, 1970). Maximum likelihood estimates (Ogata, 1983) of the parameters in (7) yield $K=2.82\pm0.69$ and $p=0.74\pm0.05$ for the distribution of the 68 aftershocks with $M_L \geqslant 2.5$ occurring in the 0.08 hour to 1540 hour interval (through June 30, 1984) following the mainshock. The corresponding variance of $n(t)$ in (7) is given by

$$\sigma^2_{n(t)} = 0.483t^{-1.48} - 0.125t^{-2.48} + 0.0106t^{-3.48}\,. \tag{8}$$

The advantage of the maximum likelihood estimation procedure is that it is based directly on the time series of aftershocks rather than on the number of aftershocks per hour.

The rate of seismicity as a function of time and the corresponding 95 percent confidence interval is given in Figure 7 for the aftershock sequence. The background rate of seismicity r from 1943 to 1982 along a 33 km segment of the Calaveras Fault, that spans the source region of the 1984 Halls Valley earthquake sequence, is $r=3.82\pm0.313$ earthquakes per year with $M_L \geqslant 2.5$. If the 1984 sequence continues to decay at its present rate it will take 17 ± 5.8 years to reach the background rate of seismicity and 243 ± 59 earthquakes with $M_L \geqslant 2.5$ will have occurred in the sequence.

Study of the 10 largest aftershocks (see Table 1) allows some inferences to be made about the sequence. The computed focal depths range from 4.7 km to 10.4 km and suggest a fault rupture of 26 km approximately along a plane striking N26°W dipping a few degrees to the east. Most of the aftershocks occurred beneath the San Felipe Valley where the Calaveras Fault has a right stepping bend (a right step in a right lateral strike-slip system reduces the normal traction acting across the fault zone and "unpins" the fault so that aftershocks are likely to occur near the bend) and at the southern end of the aftershock zone between Anderson Lake and Coyote Lake (see Table 1 and Figure 5). No aftershocks with $M_L \geqslant 2.5$ occurred in the vicinity of the most energetic portion of the mainshock source, the region east of Anderson Lake. The Calaveras Fault zone is relatively complex east of Anderson Lake where there are subsidiary faults as indicated by the multiple fault traces in Figure 5. The seismic moments in Table 1 range from 8.0×10^{20} for an earthquake of M_L 3.5 to 6.1×10^{22} for M_L 4.5. These

values are as much as 14,000 times smaller than the mainshock seismic moment.

COMPARISON WITH THE 1979 COYOTE LAKE SEQUENCE

The Halls Valley aftershock sequence extends from the hypocenter of the April 24 mainshock to within 3 km of the Coyote Lake mainshock epicenter (see Figure 5). The recorded wave amplitudes in both the Halls Valley and Coyote Lake mainshocks together with their aftershock distributions (Figure 5; and Uhrhammer, 1980) indicate that the rupture was a dislocation moving from the respective foci southeast along the Calaveras Fault. In 1979 the Calaveras Fault ruptured for 22 km with an average fault displacement of 21 cm, while in 1984 the rupture extended for 26 km with an average fault displacement of 30 cm (Table 6). These rupture lengths are consistent with the relative magnitudes of these adjacent mainshocks. For Coyote Lake the rupture surface extends from the hypocentral depth of 6.3 km to the surface where 5 mm of displacement was observed approximately 10 km southeast of the epicenter. In the Halls Valley sequence aftershocks in the first two months occurred between 4.5 and 10.5 km in depth implying that the rupture propagated both upwards and downwards from the focus. In both mainshocks most of the slip occurred at depths greater than approximately 2-4 km.

The b-value for the Halls Valley and Coyote Lake sequences are not significantly different at the 95% confidence level (Table 6). Also both b-values do not differ significantly from the estimate of b=0.78 in equation (3) for the historical seismicity between 1943-1982. In the Halls Valley sequence there were 22 aftershocks with $M_L \geqslant 3.0$ in the first ten days compared with 14 aftershocks in the Coyote Lake sequence.

The spatial distribution of Coyote Lake aftershocks (Uhrhammer, 1980) shows that the first six aftershocks with $M_L \geqslant 2.4$ proceeded along the fault progressively southeast of the mainshock and that the majority of the aftershocks clustered near the southern end of the aftershock zone. Near the southern end there are a number of subsidiary faults splaying out from the main Calaveras Fault and perhaps these complexities in the fault trace form a barrier to southward rupture propagation. The spatial distribution of Halls Valley aftershocks shown in Figure 5 shows a clustering of aftershocks beneath the San Felipe Valley where the fault has a bend, a lack of aftershocks along the eastern edge of Anderson Lake where the second source occurred and a cluster of aftershocks at the southern end of the aftershock sequence.

Figures 3 and 4 show the 100X torsion seismograms recorded at Berkeley(BRK) and the ULP displacement seismograms recorded at BKS respectively. These important multicomponent records clearly demonstrate the complexity of the Halls Valley mainshock compared to the Coyote Lake mainshock, especially since the focal mechanisms and propagation paths are quite similar for both earthquakes. In Figure 3 the Coyote Lake mainshock P-wave is an impulsive large amplitude phase in sharp contrast to the emergent small amplitude initial P-wave from the Halls Valley focus. The largest amplitudes on the Coyote Lake seismograms are clearly associated with the S_g-wave arrival from the focus, arriving approximately 13 seconds after P and 2 seconds after the initial S arrival. For Halls Valley the largest amplitude occurs 21 seconds after the initial P-wave although the S-P time is only 10 seconds.

A comparison of the two vertical seismograms in Figure 4 again shows the complexity of the Halls Valley mainshock. A large fairly impulsive arrival (at point P2) from a later source arrives 7.3 seconds after the small emergent P-wave (at point P1). If we assume that this later source also generates as an S-wave the largest amplitude observed on the 100X torsion seismograph in Figure 3 then the calculated S-P time of 13.7 seconds places the source 32 km southeast of the mainshock beyond the extent of the aftershock zone. However, if we assume a 2 second delay from the initial S-wave arrival to the peak motion as observed for the Coyote Lake mainshock (Figure 3) then the S-P time of 11.7 seconds places the later source 15 km southeast of the epicenter in agreement with the finding of Bakun et al., (1984).

The Richmond Field Station(RFS) array of downhole accelerometers recorded both the Halls Valley and the Coyote Lake mainshocks. Three triaxial accelerometer records were obtained in a vertical borehole. The accelerometers were located on the surface, at a depth of 15m and at a depth of 45m in silts and sands above the shale basement in which the lowest instrument was placed. Recorded ground accelerations are low, about one percent g, however a spectral ratio (Figure 8) of the P-wave portion of the accelerograms recorded from the Halls Valley and Coyote Lake mainshocks (Halls Valley/Coyote Lake) exhibits a harmonically modulated structure. Spectral peaks occur at 0.8Hz and 2.6Hz while spectral nulls occur at 1.5Hz and 3.4Hz. A least-squares fit of these four frequencies to a harmonic series gives a fundamental frequency of 0.83 ± 0.037Hz. Thus the fundamental and the third harmonic (odd orders) are peaks excited preferentially over the even harmonics. The primary contribution to the odd-order spectral modulation is the portion of the Halls Valley mainshock source where the moment rate is the largest (at point P2 in Figure 4). The width of the triangular P2 displacement pulse is 0.6 sec and this pulse in the time domain is equivalent to an odd-order acceleration spectra with a fundamental frequency of 0.83Hz.

A scenario for the rupture process of the Halls Valley mainshock is relatively complex. The rupture initiated at a depth of 8.2 km beneath Halls Valley as shown in Figure 5 and propagated unilaterally to the southeast along the Calaveras Fault. At the northern end of the San Felipe Valley, approximately 5 km southeast of the epicenter, the rupture encountered a right stepping bend that reduced the normal traction acting across the fault surface. The rupture continued to the southeast until it encountered a region of complexity in the fault zone, as indicated by the multiple fault traces east of Anderson Lake. The large P2 displacement pulse observed on the vertical component of the ULP shown in Figure 4 was radiated in this region. Since displacement is proportional to moment rate, an integration over the 0.6 second duration pulse implies that approximately 95 percent of the total moment of the mainshock originated in this region. The time interval of 7.3 seconds between P1 and P2 in Figure 4 implies that the average rupture velocity is at least 3.2 km/sec, roughly 90 percent of the shear wave velocity. The short duration of the P2 pulse also suggests that most of the energy was radiated from a relatively small region of the fault zone. This suggests that the region of complex fault traces east of Anderson Lake contained a relatively high strain gradient prior to the mainshock. The rupture probably continued for approximately another 10 km until finally overlapping the northern end of the 1979 Coyote Lake rupture zone. The rupture stopped in this region due to the decrease in accumulated strain energy produced by the Coyote Lake rupture.

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TABLE 1

EARTHQUAKES IN THE HALLS VALLEY SEQUENCE WITH LOCAL MAGNITUDE 3.5 OR GREATER, APRIL 24 TO JUNE 30

DATE	ORIGIN TIME (UTC)	LONGITUDE (north)	LATITUDE (west)	DEPTH (km)	MAGNITUDE (M_L)	MOMENT, M_o (dyne-cm)
April 24	21:15:19.02 (± 0.012)	37°19.2′ (± 0.10 km)	121°41.9′ (± 0.11km)	8.2 (± 0.14)	6.2 (± 0.20)	1.1×10^{25}
April 24	21:20	37°15′ IN	121°40′ CODA	8	3.6 (± 0.19)	
April 24	21:24:43.2 (± 0.043)	37°16.7′ (± 0.34 km)	121°40.4′ (± 0.39 km)	8.5 (± 0.54)	3.5 (± 0.21)	8.0×10^{20}
April 24	22:13:58.2 (± 0.012)	37°13.4′ (± 0.09 km)	121°36.6′ (± 0.11 km)	10.4 (± 0.16)	3.5 (± 0.30)	4.8×10^{21}
April 26	00:42:26.6 (± 0.048)	37°08.4′ (± 0.21 km)	121°34.8′ (± 0.27 km)	4.7 (± 0.59)	3.6 (± 0.16)	4.0×10^{21}
April 26	06:29:51.9 (± 0.076)	37°08.3′ (± 0.34 km)	121°34.2′ (± 0.44 km)	4.8 (± 0.94)	3.6 (± 0.31)	8.1×10^{21}
April 27	04:10:23.9 (± 0.046)	37°07.3′ (± 0.24 km)	121°32.7′ (± 0.30 km)	7.2 (± 0.62)	3.5 (± 0.16)	3.1×10^{21}
April 27	16:48:34.1 (± 0.043)	37°16.6′ (± 0.36 km)	121°40.2′ (± 0.41 km)	9.9 (± 0.55)	3.6 (± 0.29)	1.0×10^{21}
May 3	13:07:11.8 (± 0.016)	37°17.2′ (± 0.24 km)	121°40.1′ (± 0.15 km)	9.8 (± 0.20)	4.5 (± 0.01)	6.1×10^{22}
May 17	08:43:03.6 (± 0.033)	37°17.8′ (± 0.24 km)	121°41.3′ (± 0.26 km)	6.0 (± 0.39)	3.5 (± 0.36)	3.2×10^{21}
June 5	16:56:20.8 (± 0.050)	37°16.1′ (± 0.31 km)	121°36.6′ (± 0.39 km)	5.8 (± 0.61)	4.2 (± 0.07)	2.9×10^{22}

TABLE 2

LARGE ($M_L \geqslant 6$) HISTORICAL EARTHQUAKE SEQUENCES

DATE	TIME (UTC)	M_L	LATITUDE (°north)	LONGITUDE (°west)	COMMENTS
20 JUN 1897	20:14	6.2[2]	37.0	121.5	Coyote Lake
31 MAR 1897	07:43	6.2[2]	38.2	122.4	Mare Island
18 APR 1906	13:12	8.3[1]	37.7	122.5	San Francisco
01 JUL 1911	22:00	6.2[3],6.6[4]	37.3	121.7	Coyote
22 OCT 1926	12:35	6.1[3,4]	36.6	122.4	Monterey Bay
22 OCT 1926[5]	13:35	6.1[3,4]	36.6	122.2	Monterey Bay
24 APR 1984	21:15	6.2	37.3	121.7	Halls Valley

1 - M_S (Bolt, 1968)
2 - from Toppozada, Real and Parke, 1981
3 - from Toppozada and Parke, 1982
4 - from Bolt and Miller, 1975
5 - this earthquake is considered to be part of the sequence that began with the 12:35 October 22, 1926 earthquake

TABLE 3

HALLS VALLEY MAINSHOCK LOCATION PARAMETERS			
STATION[1]	ADJUSTMENT[2] (sec)	PHASE	P ONSET TIME (hr:min:sec)
MHC	0.01	iPd	21:15:20.90
GCC	0.19	iPd	21:15:26.75
PCC	-0.30	iPc	21:15:29.95
SAO	0.17	iPd	21:15:30.70
BRK	0.09	iPd	21:15:32.70
LLA	-0.56	iPc	21:15:35.60
PRS	-0.15	iPd	21:15:37.30
JAS	0.19	iPc	21:15:40.00

1 - station locations are shown in Figure 1 or in Bolt and Miller, 1975
2 - time to be added to the observed P onset time

TABLE 4

LOCAL MAGNITUDE OF THE HALLS VALLEY MAINSHOCK					
STATION	DISTANCE (km)	AZIMUTH (degree)[1]	COMPONENT	MAXIMUM TRACE AMPLITUDE (mm)	M_L
BERKELEY (BKS)	79	167	100X N	57.0	6.3
			100X E	37.0	6.1
MINERAL (MIN)	340	210	N	73.8	6.0
			E	69.5	5.9
ARCATA (ARC)	450	191	N	33.0	6.3
			E	40.0	6.4
COTTONWOOD (CWC)	340	39	N	110.0	6.2
PASADENA (PAS)	480	19	N	44.2	6.4
			E	57.0	6.5
RIVERSIDE (RVR)	540	24	N	16.5	6.1
			E	39.0	6.5

1 - the azimuth is measured clockwise from the direction of rupture propagation (S64°E) along the Calaveras Fault

TABLE 5

DIFFERENCE (d) FOR STRIKE-SLIP EARTHQUAKES					
DATE (MAINSHOCK)	M_L^1	M_L^2	DIFFERENCE (d)	P(d⩾D) (percent)	COMMENT
09 JAN 1857	7.9[3]	6[4]	1.9	5.3	Fort Tejon
18 APR 1906	8.3[5]	5–5.5[6]	2.8-3.3	0.4-1.0	San Francisco
09 APR 1968	6.4[7]	5.2[7]	1.2	19.7	Imperial Valley
26 NOV 1976	6.3[7]	4.2[7]	2.1	3.6	Off-shore
06 AUG 1979	5.8[7]	4.4[7]	1.4	13.6	Coyote Lake
15 OCT 1979	6.6[7]	5.4[7]	1.2	19.7	Imperial Valley
08 NOV 1980	6.9[7]	5.4[7]	1.5	11.2	Off-shore
24 AUG 1984	6.2[8]	4.5[8]	1.7	7.7	Halls Valley

1 - Local magnitude of the mainshock
2 - Local magnitude of the largest aftershock
3 - Moment magnitude from Hanks and Kanamori, 1979
4 - from Agnew and Sieh, 1978
5 - M_S from Bolt, 1968
6 - estimated from Lawson, 1908 and Ellsworth et al., 1981
7 - from the Bulletins of the U. C. Seismographic Stations
8 - this report

TABLE 6

COMPARISON OF THE HALLS VALLEY AND COYOTE LAKE EARTHQUAKE SEQUENCES		
	HALLS VALLEY (1984)	COYOTE LAKE (1979)
M_L (mainshock)	6.2	5.8
M_L (largest aftershock)	4.5	4.4
MOMENT, M_o	1.1×10^{25} dyne-cm	6.0×10^{24} dyne-cm
b-value	0.82 ± 0.10	0.70 ± 0.17
p-value	0.74 ± 0.05	1.00 ± 0.016
RUPTURE LENGTH	26 km	22 km
AVERAGE FAULT DISPLACEMENT	30 cm	21 cm
MAINSHOCK DEPTH	8.2 km	6.3 km
AFTERSHOCK DEPTHS ($M_L \geqslant 3.5$)	4.7-10.4 km	0.2-5.9 km
Number of aftershocks with $M_L \geqslant 3.0$ in the first ten days	22	14

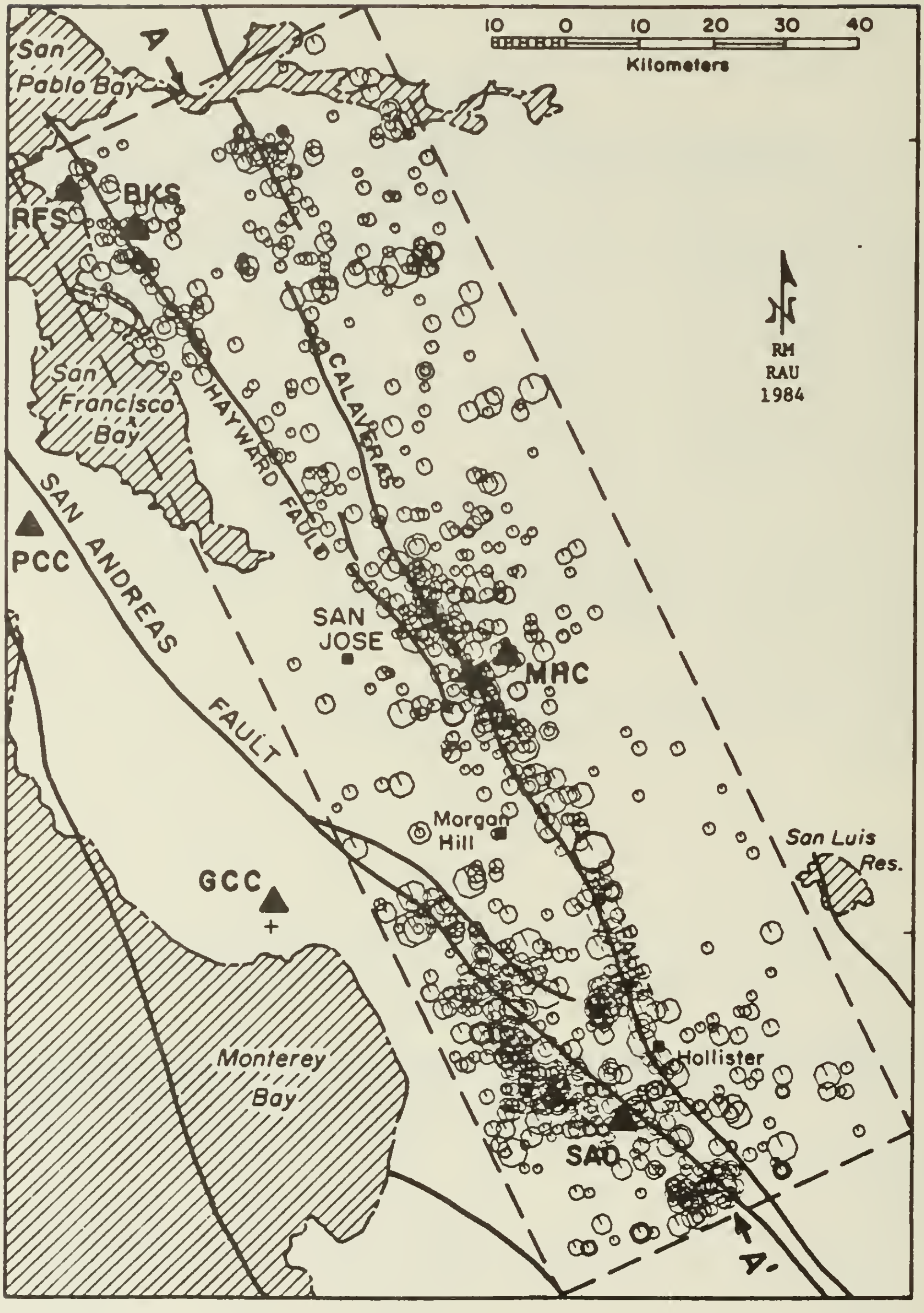

Figure 1: Historical earthquake epicenters ($2.5 \leqslant M_L \leqslant 5.8$) 1943 through 1982 in a region 50 km wide by 170 km long centered on the Calaveras Fault. The 24 April 1984 mainshock location is shown as a full star. The 6 August 1979 Coyote Lake mainshock location is shown by the heavy lined octagon east of Morgan Hill. Symbol size is proportional to local magnitude. The full triangles are permanent U. C. Seismographic Stations. The major faults are shown as solid lines.

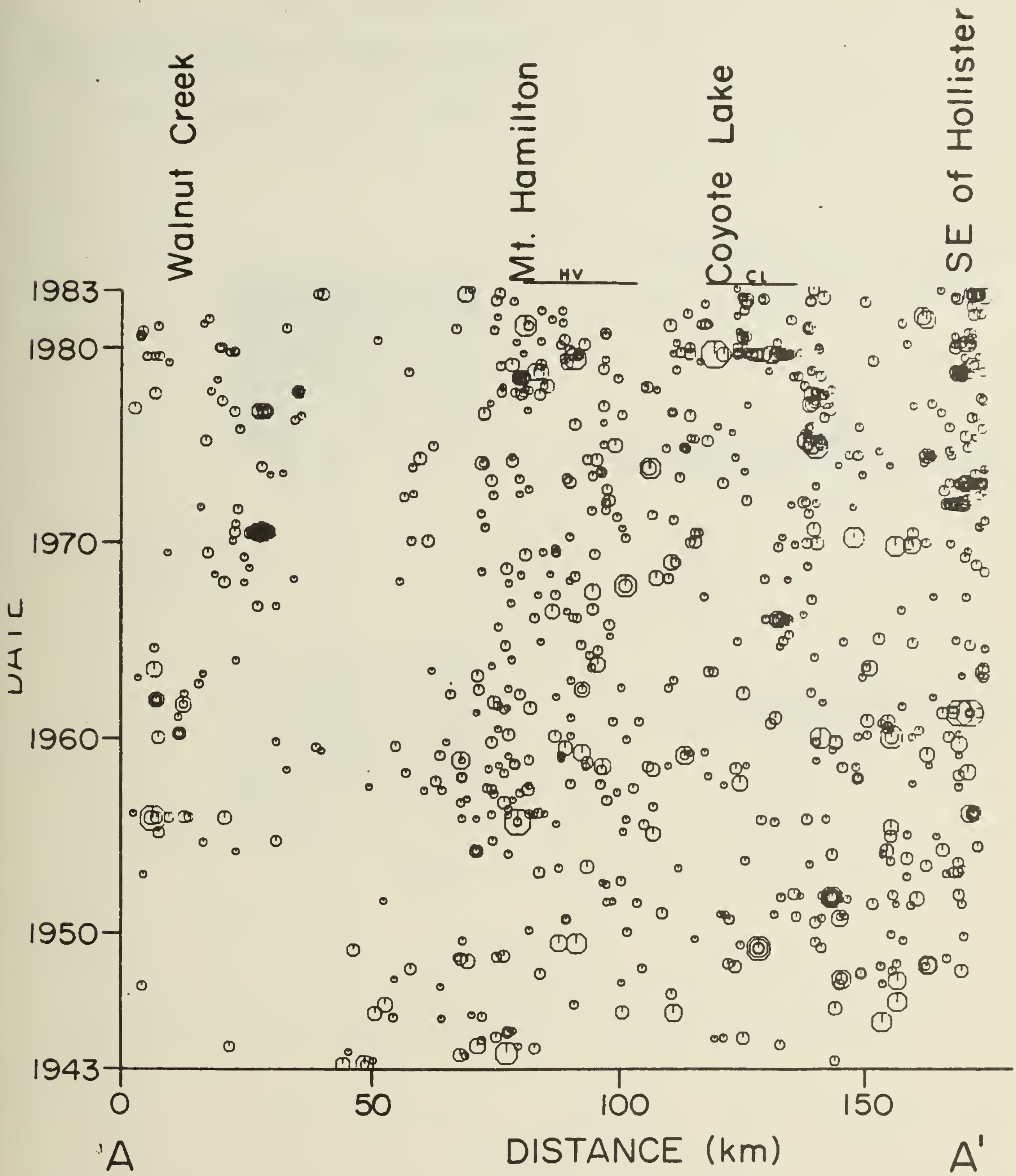

Figure 2: Space-time plot of the historical seismicity with $M_L \geqslant 2.5$ within 6 km of the Calaveras Fault from Hollister to Walnut Creek from 1943 through 1982. The extent of the Halls Valley (HV) and the Coyote Lake (CL) sequences are shown by bars at the top of the figure. Points A and A′ are shown on Figure 1. Symbol size is proportional to local magnitude.

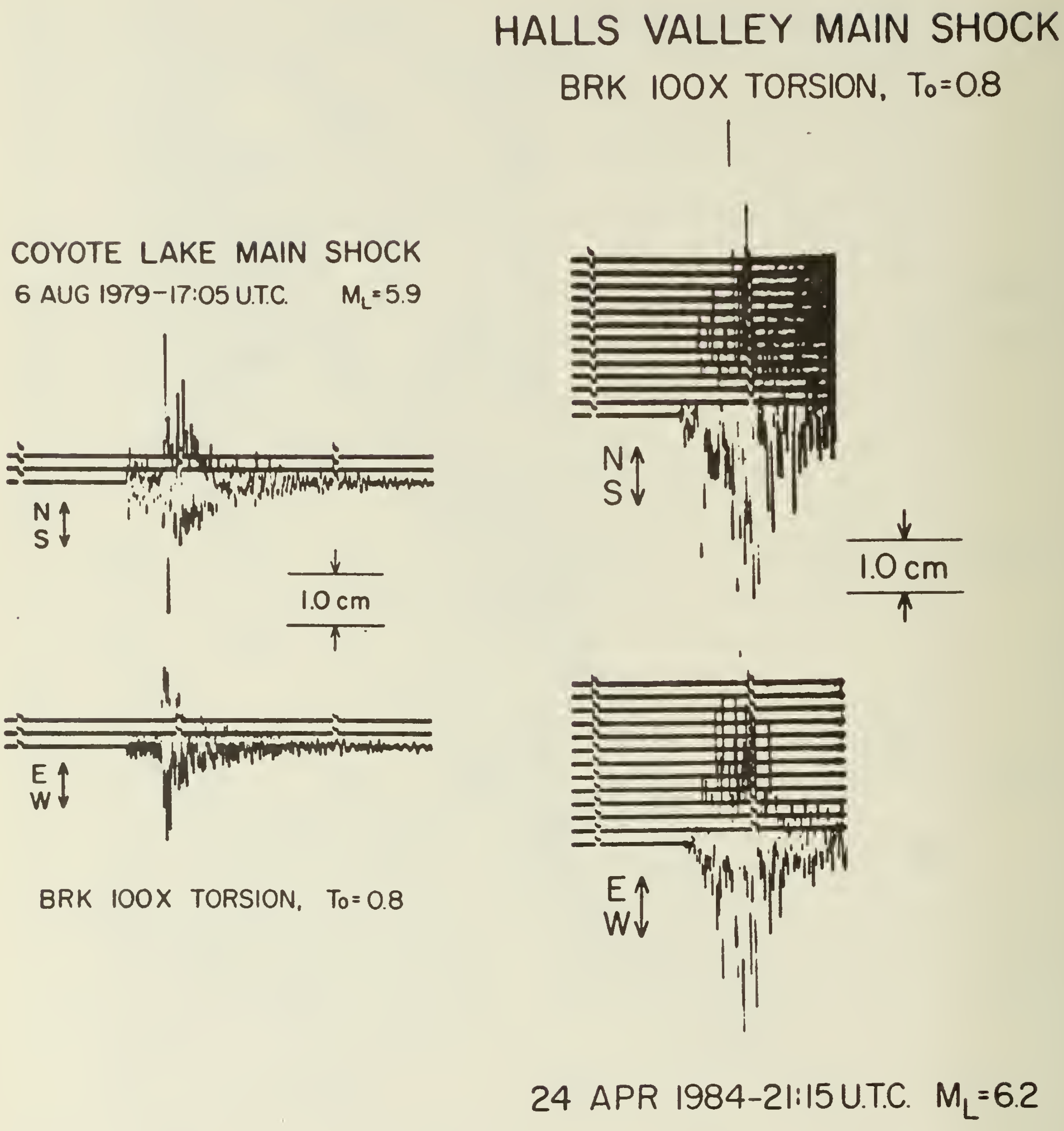

Figure 3: Seismogram recorded by a 100X torsion seismograph at Earth Sciences Building, U. C. Berkeley for the 1979 Coyote Lake mainshock (left) and the 1984 Halls Valley mainshock (right). The motion is in the N-S horizontal direction (top) and in the E-W direction (bottom). Offsets are one minute apart.

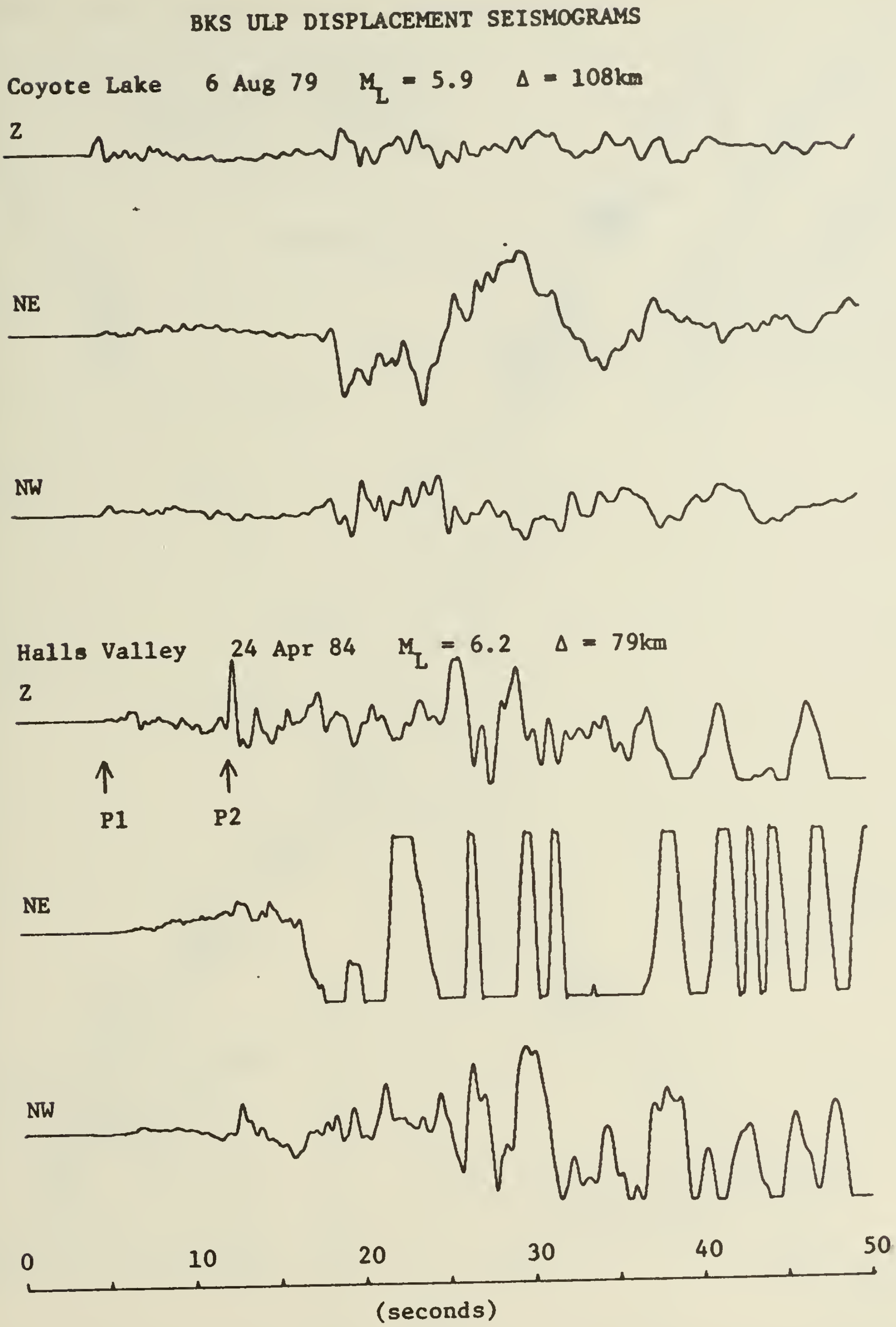

Figure 4: Ultra-Long-Period (ULP) triaxial displacement seismograms recorded at Berkeley (BKS) for the Coyote Lake mainshock (top) and the Halls Valley mainshock (bottom). The P-wave arrival from the hypocenter of the Halls Valley mainshock is shown at point P1. The large impulsive arrival from the second source located east of Anderson Lake is shown at Point P2. The record length is 50 seconds and time ticks are 5 seconds apart. The peak to peak clipping level is 4mm.

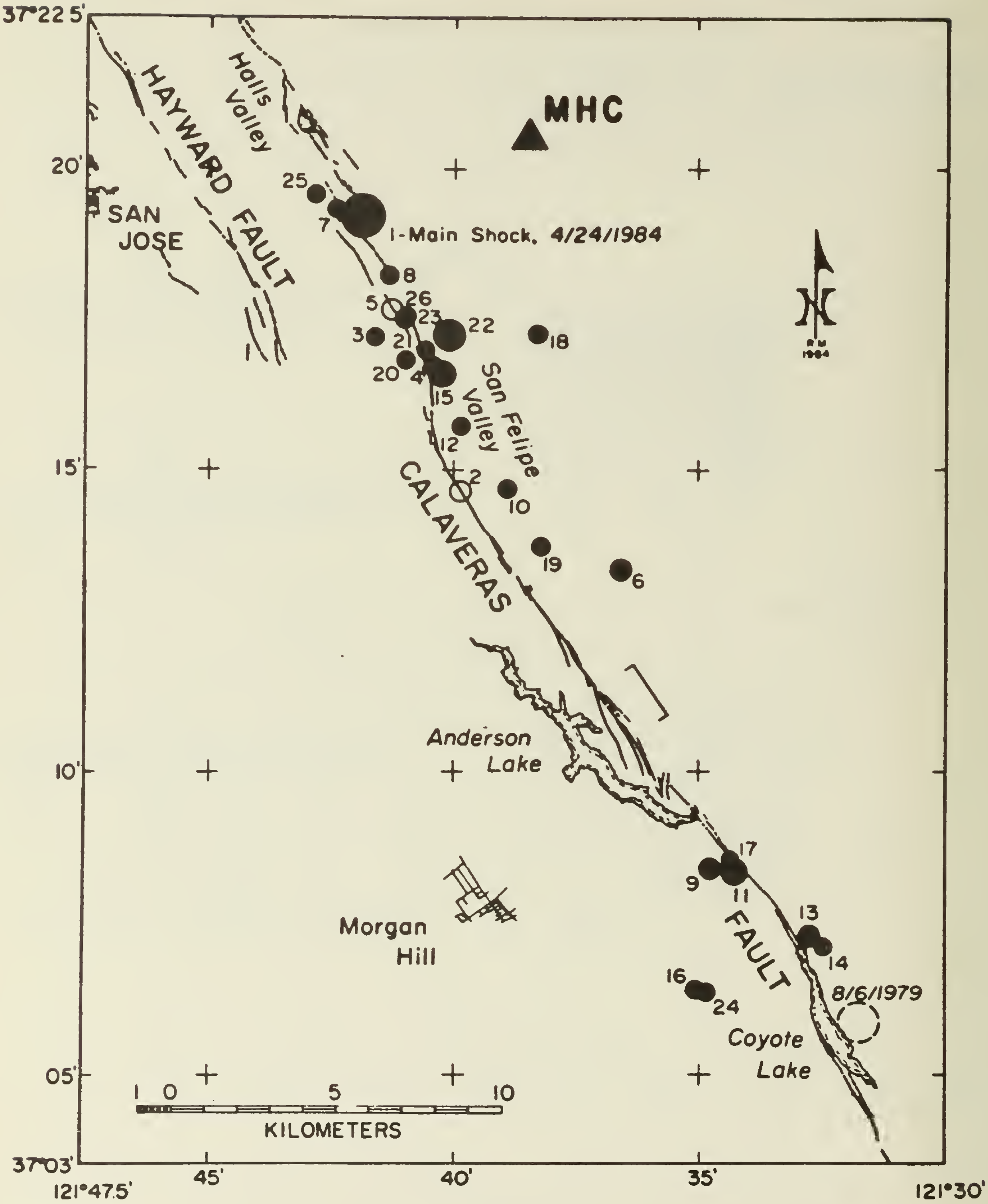

Figure 5: Epicenters of the mainshock of 24 April 1984 and principal aftershocks ($M_L \geqslant 3.0$) through 17 May 1984 are plotted as numbered circles whose diameter scales to local magnitude. The numbering indicates the relative timing of the earthquakes in the sequence. The two small open circles are the locations of aftershocks located using only the differential arrival times at BKS and SAO because these events occurred in the coda of a preceding earthquake. The Coyote Lake 1979 mainshock is plotted as a large broken circle. The location of the later source is delimited by a square bracket east of Anderson Lake.

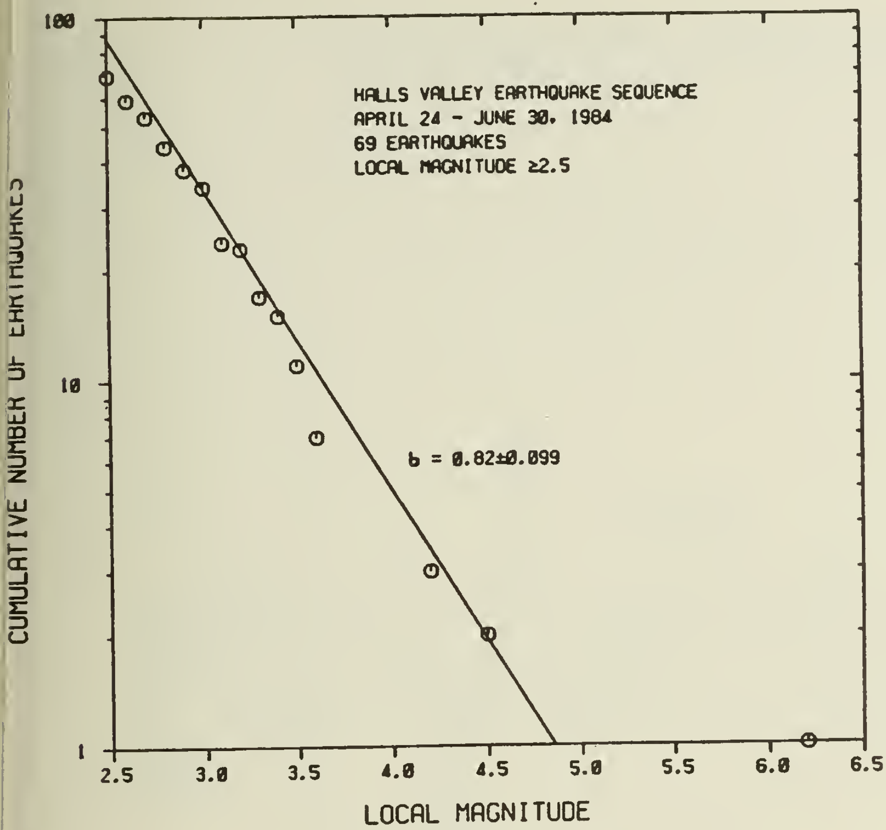

Figure 6: Cumulative number of earthquakes as a function of local magnitude for the Halls Valley earthquake sequence of April 24 through June 30, 1984.

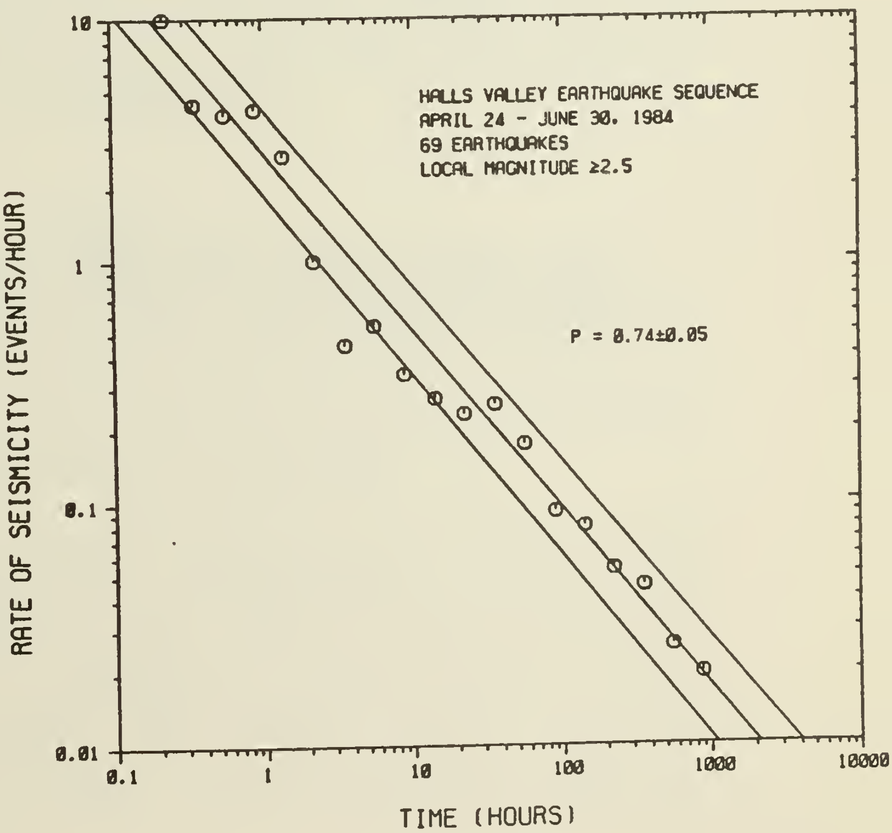

Figure 7: Rate of seismicity versus time for the Halls Valley earthquake sequence April 24 through June 30, 1984. The maximum likelihood estimate for the rate of seismicity as a function of time along with the 95 percent confidence interval are plotted.

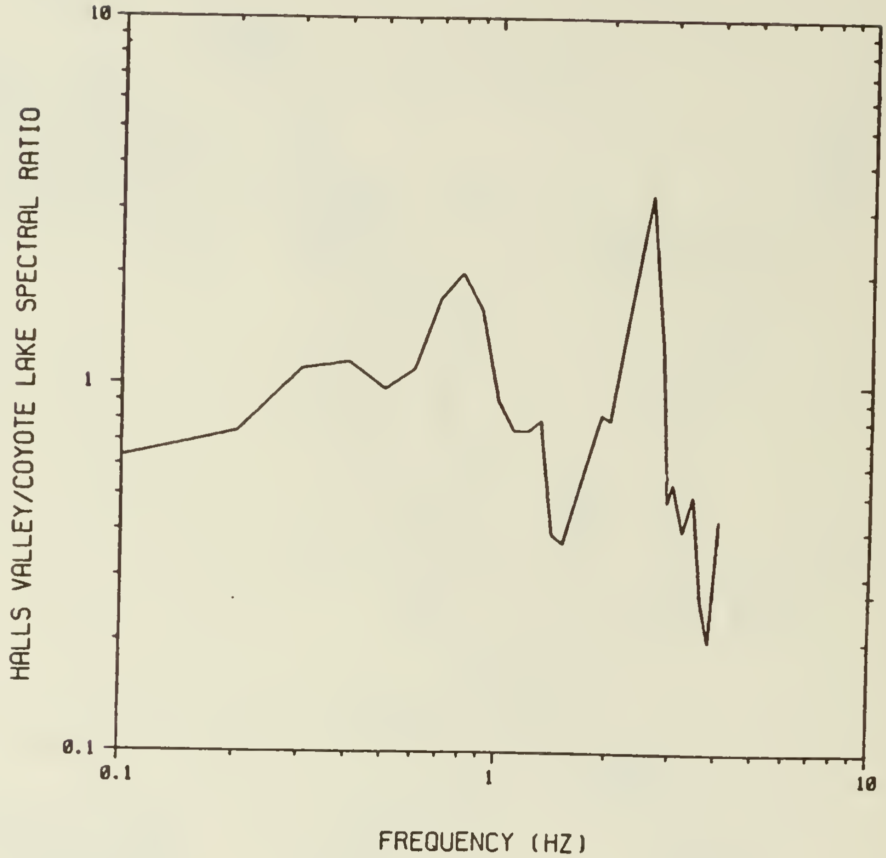

Figure 8: Spectral ratio of the P-wave window of a horizontal accelerogram recorded at RFS (ground level) for the Halls Valley mainshock/ Coyote Lake mainshock from 0.1 Hz to 4 Hz.

CENTROID-MOMENT TENSOR SOLUTION FOR THE APRIL 24, 1984 MORGAN HILL, CALIFORNIA, EARTHQUAKE

by

Göran Ekström[1]

ABSTRACT

Seismic records from the GDSN network are used to obtain long-period (T > 45 sec.) source parameters for the April 24, 1984, Morgan Hill, California earthquake, employing the Centroid Moment Tensor method of Dziewonski, Chou, and Woodhouse (1981), and Dziewonski and Woodhouse (1983). The favoured double-couple mechanism is: strike = 333°, dip = 90°, rake = 180°, seismic moment = $2.0*10^{25}$ dyne-cm.

INTRODUCTION

The April 24, 1984, Morgan Hill, California earthquake was well recorded on the Global Digital Seismological Network and suited for routine analysis by the centroid moment tensor method. We report first order fault parameters obtained for this event.

ANALYSIS

The centroid moment tensor (CMT) method is described in detail by Dziewonski, Chou, and Woodhouse (1981), and Dziewonski and Woodhouse (1983). Briefly, the method consists of the inversion of waveform data for the simultaneous determination of the six independent components of the moment tensor and the centroid, where the centroid is equivalent to the point source location in space and time which, together with the moment tensor, best explains the observed seismogram.

Long-period body-waves from the GDSN network were low-pass filtered with a cut-off period of 45 seconds. The records were truncated before the arrival of the fundamental mode surface waves. The synthetic seismograms used in the inversion were obtained through summation of the Earth's normal modes. All modes with periods greater than 45 seconds were used (approximately 5000) and a heterogeneous upper mantle model (Woodhouse and Dziewonski, 1984) was used in the calculation

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(Dziewonski et. al., 1984). The CMT solution was obtained by an iterative least-squares fitting of the waveform data and the synthetic seismograms.

Figure 1 shows azimuthal station coverage for the analysis. 29 vertical and horizontal body-wave records from 11 stations were used in the inversion. Figure 2 shows fits between observed and synthetic seismograms for the favoured solution.

The source depth was fixed at 10 kilometers. The source half-duration was estimated at 4.7 seconds from the simple scaling relationship

$$T = 1.7*10^{-8}*M_0{}^{1/3}$$

derived from Kanamori and Anderson (1975) where M_0 is the scalar moment in dyne-cm and T is the half-duration in seconds.

The components $M_{r\theta}$ and $M_{r\phi}$ of the moment tensor, corresponding to vertical dip-slip faulting, are poorly constrained in the inversion for shallow sources. We therefore performed two inversions, with and without the constraint $M_{r\theta} = M_{r\phi} = 0$, and used ad hoc standards to determine which solution to prefer. We used the same criterion as Ekström and Dziewonski (1984) in their CMT-analysis of Californian earthquakes, that a variance reduction of 0.006 of the unconstrained solution with respect to the constrained is significant enough to render the unconstrained solution preferable.

Source parameters for the two inversions are given in Tables 1 and 2 and Figure 3. Since the difference in variance between the two iterations is small (0.003) we favour the constrained solution. The 'best double-couple' solution corresponds to setting the intermediate eigenvalue of the moment tensor equal to zero. The relative smallness of the intermediate eigenvalue with respect to the maximum and minimum eigenvalues (< 7% for the favoured solution) indicates that the source is well described by one single double-couple.

CONCLUSIONS

The mechanism of the 1984 Morgan Hill earthquake determined by a centroid-moment tensor analysis of long-period body-wave seismograms is found to be well described by a single double-couple. The prefered solution corresponds to pure right-lateral strike-slip motion on a fault striking 333°. The minor double-couple contribution to the moment tensor is less than 7% of the total seismic moment.

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Figure 1 - Azimuthal equidistant plot centered on the Morgan Hill earthquake. Dashed lines connect the epicenter with stations that were used in the analysis.

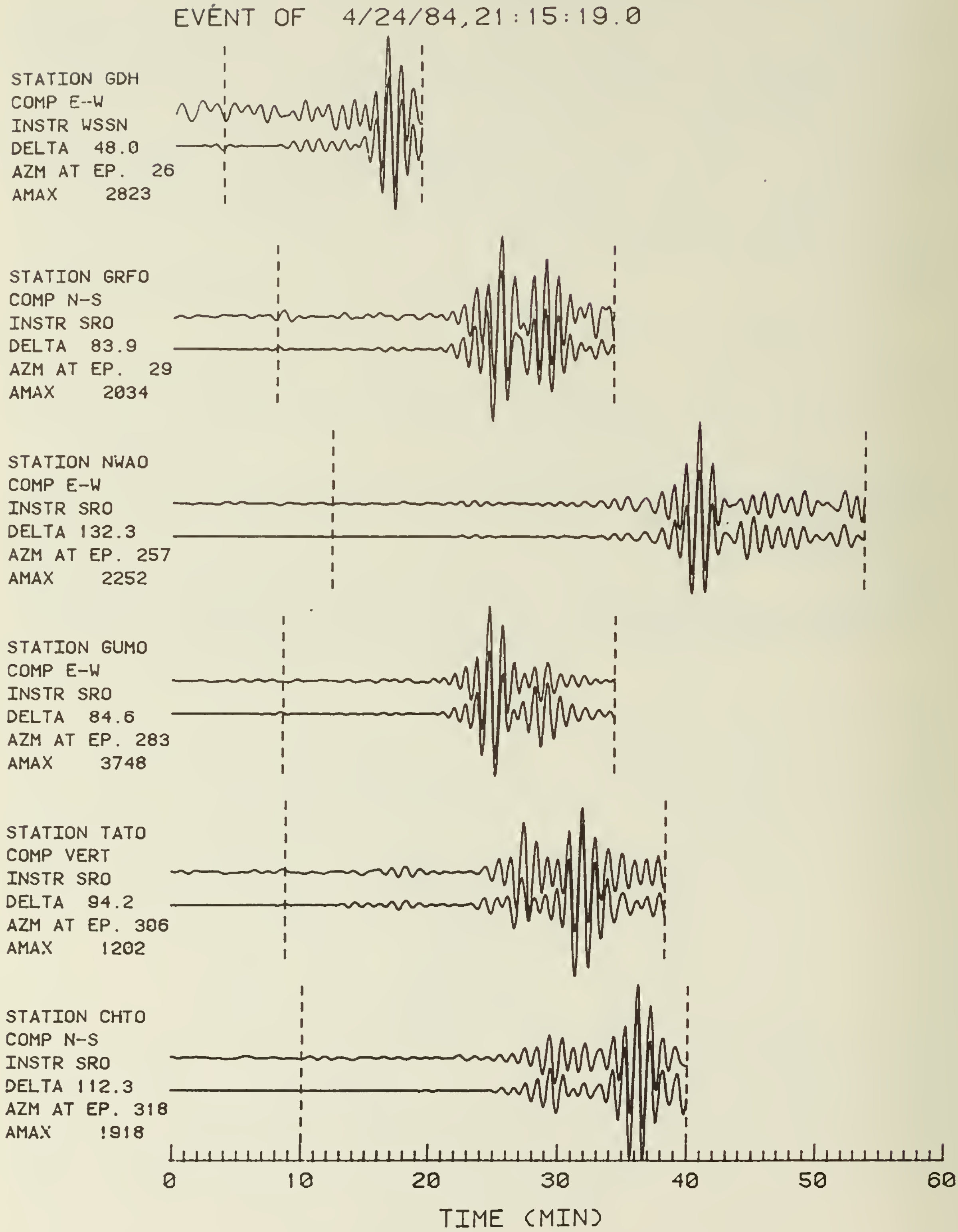

Figure 2 - Comparison between observed waveform data (top trace) and synthetic seismograms (bottom trace) for different stations. Only data between the vertical lines are included in the inversion.

Table 1

Inversion Results (Unconstrained)

(Depth 10.0 km, Source Half-Duration = 4.7 sec)

Centroid Location

Origin Time	21:15:28.8 (±0.3 sec)
Latitude	37.59° (∓0.03°)
Longitude	-122.16° (∓0.03°)

Moment Tensor Components ($*10^{25}$ dyne-cm)

M_{rr}	-0.139 (±0.028)
$M_{\theta\theta}$	-1.579 (∓0.043)
$M_{\phi\phi}$	1.718 (∓0.032)
$M_{r\theta}$	0.418 (∓0.100)
$M_{r\phi}$	0.311 (∓0.102)
$M_{\theta\phi}$	1.195 (∓0.028)

Principal axes ($*10^{25}$ dyne-cm)

	Value	Plunge	Azimuth
1. (T)	2.18	10°	288°
2. (N)	-0.17	76°	66°
3. (P)	-2.02	9°	196°

Nodal Planes of Best Double-Couple

	Strike	Dip	Rake
1.	333°	76°	179°
2.	63°	89°	14°

Scalar Moment of Best Double-Couple

$M_0 = 2.1*10^{25}$ dyne-cm

Variance = 0.277

(Quantities in brackets are standard errors)

Table 2

Inversion Results (Constrained)

(Depth 10.0 km, Source Half-Duration = 4.7 sec)

Centroid Location

Origin Time	21:15:28.8 (±0.3 sec)
Latitude	37.59° (∓0.03°)
Longitude	-122.25° (∓0.02°)

Moment Tensor Components ($*10^{25}$ dyne-cm)

M_{rr}	-0.134 (±0.028)
$M_{\theta\theta}$	-1.580 (∓0.043)
$M_{\phi\phi}$	1.715 (∓0.032)
$M_{r\theta}$	0.000
$M_{r\phi}$	0.000
$M_{\theta\phi}$	1.185 (±0.029)

Principal axes ($*10^{25}$ dyne-cm)

	Value	Plunge	Azimuth
1. (T)	2.10	0°	108°
2. (N)	-0.13	90°	180°
3. (P)	-1.96	0°	18°

Nodal Planes of Best Double-Couple

	Strike	Dip	Rake
1.	333°	90°	180°
2.	63°	90°	0°

Scalar Moment of Best Double-Couple

$M_0 = 2.0*10^{25}$ dyne-cm

Variance = 0.280

(Quantities in brackets are standard errors)

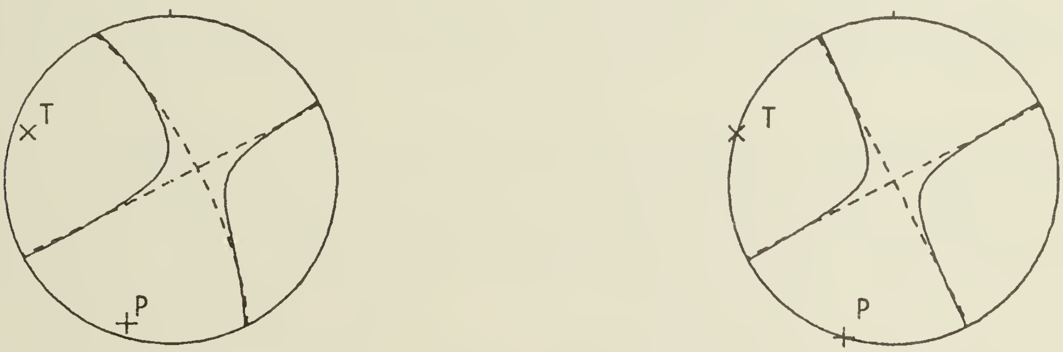

Figure 3 - Unconstrained and constrained focal mechanisms for the Morgan Hill earthquake. The full moment tensor (solid lines) and the 'best double-couple' (dashed lines) are shown. For both representations the lines separate the expected compressional first P-wave arrivals from the dilatational on the focal sphere. The plots are equal-area, lower hemisphere projections.

THE APRIL 24, 1984 MORGAN HILL EARTHQUAKE AND ITS AFTERSHOCKS: APRIL 24 THROUGH SEPTEMBER 30, 1984

by

Robert S. Cockerham[1] and J. P. Eaton[1]

ABSTRACT

Aftershocks of the Morgan Hill earthquake clearly outline a near-vertical fault surface that is parallel to but much simpler in structure than the mapped strands of the Calaveras Fault in the aftershock region. A central quiet zone in the aftershock pattern on the inferred fault surface marks out adjacent 3 km x 10 km and 5 km x 13 km patches that are believed to be the rupture region of the main shock. The transition between these patches coincides with a 6° change in strike of the inferred fault surface. A prominent group of aftershocks southwest of the principal band of aftershocks appears to be bounded by the Calaveras Fault on the northeast and by the Silver Creek (or related, reverse) Fault below and on the southwest. These aftershocks suggest that the Morgan Hill earthquake was accompanied by, or stimulated, movement on one or more nearby reverse faults.

INTRODUCTION

On April 24, 1984 at 2115 18.8 UTC an M6.2 earthquake occurred on the Calaveras Fault about 20 km east of downtown San Jose, California (Fig. 1a). This earthquake was felt throughout central California (Bakun et. al., 1984). Because of the concentration of damage in a suburb of the town of Morgan Hill, this earthquake has been called the Morgan Hill earthquake (Bakun et. al., 1984).

The work reported in this paper is based primarily on data recorded by the USGS northern California seismic network and processed by a computer assisted interactive seismic analysis system. For the main shock, however, P-wave onset times and first-motion directions as well as maximum amplitudes and associated periods were read from magnetic tape playbacks from northern and southern California network stations. The principal objectives of this report are:

(1) to develop a one-dimensional velocity model and associated station corrections for use in locating earthquakes in the Morgan Hill region,
(2) to determine the hypocenter, local magnitude, and fault plane solution of the main shock, and
(3) to determine the distribution of the aftershock hypocenters.

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SEISMIC NETWORK

The USGS seismic network in the Morgan Hill area is composed primarily of high-gain short-period vertical component seismic systems (Fig. 1a). Several low-gain seismic systems at the northern and southern ends of the network wrote unclipped records of the main shock from which maximum amplitudes and associated periods were measured. During the first 2 days after the main shock, additional seismic stations (Fig. 1b) were installed in the aftershock region to augment the network.

The progress of aftershock activity was monitored in Menlo Park by means of locations provided by the Allen/Ellis real-time processor (RTP; Allen, 1978). The RTP located several hundred earthquakes, with 30 to 40 reporting stations per event, during the first 72 hours of the aftershock sequence. During the early hours of the sequence the rapid locations provided by the RTP allowed selection of the most critical sites for portable stations while the field crews were still enroute to the epicentral region.

DATA SELECTION

The telemetered data were digitized and analyzed by an improved online/offline computer assisted seismic analysis system based on an original design by Johnson (1978). The incoming signals were digitized at 100 samples per second; automatically detected seismic events were saved and demultiplexed for off-line analysis. For analysis, which was interactive, seismograms were displayed on a CRT. P- and S-wave onsets were picked and timed to 0.01 sec., and coda lengths were measured for magnitude determinations. All hypocenter determinations were carried out with program HYPO71 (Lee and Lahr, 1975).

CRUSTAL VELOCITY MODEL

The station travel-time corrections (Table 1) and the P-wave crustal velocity model (Table 2) used for this study were obtained by a full inversion of P-wave arrival times from 40 aftershocks of the Morgan Hill earthquake using a procedure written by Roecker and Ellsworth (1978) following the method of Crosson (1976). The events used in the inversion were all of $M>2.0$ and were recorded by 30 or more stations, including 10 or more of the temporary stations. They were distributed along the entire length of the aftershock zone.

The starting model for the velocity inversion was based on the results of Blumling et al. (in press.). Their crustal model for the Morgan Hill region was determined from explosion data recorded within and transverse to the Calaveras Fault zone. Their final crustal model for the region has several wedges of sedimentary material that cannot be taken into account by the location program. A composite one-dimensional model embodying the principal features of their regional model was used as a starting model in the inversion procedure of the Morgan Hill aftershock data.

We compared hypocentral determinations based on our final model with those based on two other models. Mayer-Rosa (1973) derived a model for this section of the Calaveras Fault from explosion data recorded at short distances. However, his model extends only to shallow depths (about 6 km). The second model used was developed by Ellsworth and Marks (1980). Their model is a generalized model for the region east of San Francisco Bay and was derived from explosion and earthquake data in the Livermore region. Focal depths computed with the Mayer-Rosa model are somewhat shallower, and locations computed with the Ellsworth/Marks model are somewhat more scattered than those

obtained with our model based on the Morgan Hill aftershocks. Although the overall hypocenter distribution patterns produced by the three models are very similar, we believe that the absolute locations based on the aftershock model are superior to those based on the other two models because the aftershock model was determined from a more comprehensive local set of travel-time observations than were the other two models.

THE MAIN SHOCK

The Morgan Hill earthquake occurred on the Calaveras Fault in a region of great geologic complexity. In this region the band of frequent small earthquakes believed to be associated with the Calaveras Fault is located, with the model and station corrections routinely used for central California by the USGS, about 3 km east of the surface expression of the fault. In a preliminary study of the Morgan Hill earthquake (Eaton, 1984), three different models were used to determine the hypocenter of the main shock to assess the dependence of the hypocenter on the model. The models and associated station corrections used were:

A) the standard USGS model and station corrections for the central California Coast Ranges,

B) the East Bay regional model developed by Ellsworth and Marks (1980), and

C) station corrections based on Pn time-term differences in the central Coast Ranges (Eaton, 1980, unpublished) and a crustal model designed to minimize the r.m.s. of traveltime residuals of the main shock.

The hypocenters calculated from the three models were within 1.5 km of each other in both epicenter and focal depth, but all three lay east of the surface expression of the Calaveras Fault. Distances to the nearest mapped strand of the Calaveras fault from the three epicenters were: A, 1.8 km; B, 1.1 km; and C, 0.8 km.

The hypocenter of the main shock calculated with the model and station corrections derived for use in the present study is almost identical to that from model C. It is 0.3 km shallower and 0.1 km due east of solution C. We interpret this close agreement between the results of two models derived by very different procedures as support for the validity of the result.

A plot of first motions of the main shock is shown in Figure 2. Nodal plane I strikes N34°W and dips 84°SE. Nodal plane II strikes N57°E and dips 80°NW. Nodal plane I can be confidently identified as the fault plane because it parallels the long narrow band of aftershocks as well as the Calaveras Fault.

The most seriously discordant points on the first motion plot are for stations CCO (at Δ=5.8 km) and CMH (at Δ=8.9 km). Both of these stations lie just west of the Calaveras fault and are receiving first motions appropriate for the east side of the fault. These discordant first motions as well as the apparent mislocation of the main shock and its aftershocks about 1 km east of the surface expression of the Calaveras Fault suggest that P-wave velocities at upper- and mid-crustal depths are somewhat higher east of the fault than west of it.

Three low-gain horizontal component seismometers in northern California and ten low-gain vertical component seismometers in southern California produced records from which maximum amplitudes and associated periods could be measured. The distance and azimuth of each of these stations from the epicenter

as well as the magnitude computed for it are shown in Table 3. The average M_L for the three northern California stations is 6.17. The ten M_L values from southern California average 6.74, substantially larger than the northern California average. A correction of +0.25 is added to magnitudes computed from a vertical component instead of a horizontal component seismometer to compensate for the average ratio of horizontal to vertical maximum amplitudes. This correction was determined from a limited number of small to moderate earthquakes recorded at distances less than 200 km in central California, and it may be inappropriate for larger earthquakes recorded at much greater distances.

We should also note the rather narrow range in azimuth of the stations reporting magnitudes in northern California (328 degrees to 353 degrees) and southern California (125 degrees to 134 degrees). The difference in northern and southern California magnitudes may arise from the NW to SE direction of rupture propagation in the event (Bakun et al., 1984).

The results on the Morgan Hill main shock can be summarized as follows:

Date	April 24, 1984
Time	21 15 18.78 UTC
Latitude	37° 18.56'N
Longitude	121° 40.68'W
Depth	8.42 km
M_L	6.2 (6.5 to 6.7 So. Cal.)
Fault Plane	Strike N 34° W Dip 84° SE
Auxiliary Plane	Strike N 57° E Dip 80° NW
Pressure Axis	Azimuth 191° Dip 3°
Movement	Right lateral strike slip

SPATIAL DISTRIBUTION OF THE AFTERSHOCKS

The Morgan Hill earthquake and its aftershocks from April 24 through Sept 30, 1984 are plotted in Figure 3. Magnitudes and focal depths are indicated by the size and letter code of the plotting symbols, respectively. The faults shown in Figure 3 are from Herd (1982). Selected localities and physiographic features are also shown as an aid to orientation.

The primary feature of the aftershock pattern is the narrow central band of aftershocks that runs parallel to the trend of the Calaveras Fault zone from Halls Valley on the northwest to the north end of Coyote Lake on the southeast. This band is generally less than 1 km wide and more than 30 km long. Notable secondary features of the aftershock distribution include:

1) three 5 to 7-km long north-trending alignments of shallow earthquakes that lie east of the northwestern half of the central band,
2) a 6-km-long alignment of hypocenters at a depth of 7 to 8 km that parallels the central portion of the central band southwest of San Felipe Valley and is offset 1 1/2 to 2 km southwest of it,
3) a dense 2-km-wide by 3-km-long cluster of shallow aftershocks just west of the central band at the south end of Anderson Lake.

At its northwest end the central band of aftershocks is about 1/2 km east of the mapped strands of the Calaveras Fault. In its 30+ km extension to the southeast, the central band curves very gently to the west. Nowhere does it depart more than about 1 km from the straight line striking N33°W that joins its endpoints. At the south end of Anderson Lake the central band lies 1 to 1.5 km east of the principal mapped strand of the Calaveras Fault. The mapped strands of the Calaveras Fault between Halls Valley and Coyote Lake suggest a

more complex structure than the central band of aftershocks. Between San Felipe Valley and the center of Anderson Lake the mapped strands of the fault are offset 1.5 to 2 km southwest of a line joining strands of the fault at Halls Valley on the northwest and Coyote Lake on the southeast. This offset is adjacent to the Silver Creek Fault and related faults (Page; 1982a, 1982b) which strike more westerly than the Calaveras Fault and appear to terminate at or near the Calaveras between San Felipe Valley and Coyote Lake. It also has the same sense and size as the offset of the alignment of the 7 to 8-km deep aftershocks southeast of San Felipe Valley from the central band of aftershocks. Although we note the possible systematic mislocation of the main shock and its aftershocks as well as the biasing of the dip of the fault surface corresponding to the crustal band of aftershocks that would result from P-wave velocities being higher east of the fault than west of it, we believe that the uncorrected hypocenters presented herein should be used until an independent quantitative estimate of the possible velocity difference is available.

In Figure 4 the map pattern of aftershocks at all depths (A) is compared with patterns for the depth intervals $H<2.5$ km (B), $2.5<H<7.5$ km (C), and $H>7.5$ km (D). In the pattern of shallow events (B), the central band of aftershocks is visible, but it is no more prominent than the alignments of shallow aftershocks that lie east of the northwestern half of the central band and west of the southeastern half of the central band. In the pattern of intermediate-depth aftershocks (C) the central band is well developed, and it is flanked by scattered events to the east along its northwestern half and by a more concentrated band of aftershocks to the west along most of its length, particularly from the southwest end of San Felipe Valley to the southwest end of Anderson Lake. In the pattern for deep events (D) the central band consists of several very narrow segments that can be grouped into northwestern and southeastern halves with average strikes of N35°W and N29°W, respectively. Similar changes in the strike direction of the central band occur at shallow (B) and intermediate (C) depths. Below 7.5 km depth, a subparallel band of aftershocks lies opposite and about 2 km southwest of a gap in the central band between its northwestern and southeastern halves, just southeast of San Felipe Valley.

The root of the Morgan Hill aftershock zone is narrow and simple below 7.5 km depth. The central band of aftershocks and the aftershocks southwest of that band are best expressed in the depth range of 2.5 to 7.5 km. The pattern of aftershocks above 2.5 km depth and its relationship to the mapped strands of the Calaveras Fault suggest that these aftershocks are concentrated on local shallow structures bordering the Calaveras Fault and that the Calaveras Fault does not cut cleanly through this shallow region, above the principal trace of the fault at depth, over much of the break associated with the Morgan Hill earthquake. There appears to be a small but clear change in the strike of the central band of aftershocks about 5 km southeast of San Felipe Valley, from N35° in the northwest to N29°W in the southeast.

Longitudinal cross sections of the aftershock zone in Figure 5 are projected onto a vertical plane through the line R-R' (azimuth 327°, Figure 4D). In section A aftershocks within 10 km of R-R' are included in the plot. In sections B and C only aftershocks within a 2.1 km-wide band along R-R' are included to permit aftershocks along the principal fault to be separated from those bordering the fault.

Section B shows a central area of quiet surrounded and almost completely outlined by a zone of aftershocks. The main shock hypocenter lies within the quiet zone at its northwest end. We interpret the quiet zone to be the section of the fault that slipped during the main shock and the surrounding zone of aftershocks to be the subsequent extension of the slipped region on the fault surface. Reasenberg and Ellsworth (1982) find a zone of subdued aftershock activity around the main shock of the 1979 Coyote Lake earthquake, which occurred on the Calaveras fault just southeast of the Morgan Hill aftershock zone. King et al. (in press) present evidence that the main shocks of the 1981 Corinth, Greece earthquake sequence lie between clusters of aftershocks and suggest that "de-stressed regions associated with the main event faulting are relatively free from aftershocks compared to regions where the motion on the main fault planes increased stress". Section C shows that aftershocks with $M \geq 2.0$ generally show the same pattern as in section B, but with poorer definition. The $M \geq 2.0$ aftershocks are most numerous in the distance range 1 to 7 km along the profile, which is the region just southeast of San Felipe Valley with the alignment of 7 to 8 km-deep earthquakes southwest of the central band. Section A, compared with section B, shows that the off-fault aftershocks are predominantly shallow.

Transverse cross-sections of the aftershock zone in Figure 6 are projected onto a vertical plane perpendicular to the average trend of the central band of aftershocks (azimuth 327°) and parallel to the line T-T' in Figure 4D. On section B, for aftershocks with $M \geq 2.0$, the fault surface appears as a very narrow zone of aftershocks dipping about 85° NE and passing through the main shock. Most of the off-fault aftershocks are 2 to 4 km deep and lie southwest of the fault. There appears to be a complexity in the fault between 8 and 11 km depth, centered on the main shock. On section A, which shows the entire set of aftershocks, the nearly vertical fault is the most striking feature, but the off-fault features of the pattern are also well defined. The shallow alignments of aftershocks northeast of the principal fault are well separated from it. A diffuse horizontal zone of aftershocks at 5 to 8 km depth extends out to about 8 km northeast of the fault. Aftershocks southwest of the fault are much more numerous than those northeast of it. Most of these events are concentrated in two groups, at 2 to 4 km depth and at 6 to 8 km depth, and they appear to be bounded on the southwest by a line that dips about 60°NE and outcrops about 7 km southwest of the central band of aftershocks near the Silver Creek Fault.

In Figure 7 transverse sections are shown for three zones along the fault (Fig. 4D): N(8 km<R<19 km), C(-3 km<R<8 km), and S (-19 km<R<-3 km). The N and C sections are perpendicular to an azimuth of 327° (same as in Fig. 6), but section S is perpendicular to an azimuth of 331°, reflecting the gradual change in strike of the central band of aftershocks from north to south. In all three sections the fault appears as a very narrow zone of aftershocks, but its dip changes progressively from north to south: 88°NE in section N, 84°NE in section C, and 81°NE in section S. In section N the aftershocks nearest to the main shock, at depths of 7.5 to 9 km, suggest that this part of the fault surface may dip very steeply toward the southwest, in agreement with the main shock fault plane solution.

Maps and cross sections fail to show adequately the spatial relationships of the structures defined by concentrations of hypocenters in the Morgan Hill aftershock sequence. These relationships can be shown more clearly by selected

stereo plots that view the aftershock distribution from favorable directions. The stereo plot program was provided by Reasenberg (oral communication) who had extended an earlier program by German and Johnson (1981). Each of the stereo plots in Figures 8-10 is enclosed in a frame whose central axis parallels the central band of aftershocks (azimuth 327°). The frame is 12 km in height; and 2-km intervals are drawn on one face of the frame. A 1-km reference cube with its horizontal edges aligned north-south and east-west and with its top at a depth of 5 km is plotted in the southeast corner of each frame. In map view the frames are outlined in Figure 4D. The main shock is plotted as a circle lying in the fault plane deduced from the fault plane solution and with a diameter showing the direction of slip. The aftershocks are plotted as small crosses that are scaled weakly according to magnitude.

In Figure 8A the aftershock region is seen from below: the viewing point is 50 km deep and nearly beneath the southwest corner of the frame. The main shock is the vertically oriented disc near the northwest (lower left) end of the frame and the reference cube (upper right) is in the southeast corner of the frame. Most features of the aftershock distribution described above are visible here, including the change in strike direction of the central band of aftershocks southeast of San Felipe Valley.

In Figure 8B the aftershock region is seen from above: the viewing point is 30 km above the earth's surface and nearly above the southeast corner of the frame. The main shock is near the northwest end of the frame (upper right) and the reference cube is in the southeast corner of the frame (lower right).

In Figure 9A the viewing point is at a depth of 5 km and the line of sight is northwestward along the northeast side of the fault surface. The shallow clusters northeast of the fault are clearly separated from aftershocks along the fault, but the scattered deeper events at the far end of the plot (northwest) appear to approach the fault.

In Figure 9B the viewing point is at a depth of 5 km and the line of sight is southeastward along the southwest side of the fault. Most of the off-fault events southwest of the fault are enclosed in a triangular prison with its bottom edge near the fault at a depth of about 8 km. One upper edge is along the fault (at about 2 km depth) and the other is at about the same depth and 7 km southwest of the fault. The main shock is the disc in the foreground and the reference cube is in the southeast corner of the frame (upper left).

Figure 10 shows closeup views of the three regions (N, C, and S, Fig. 4d) from viewing points near the fault surface and 5 km deep. In Figure 10A region N is seen from the southeast along the northeast side of the fault. The main shock is the disc in the lower center of the frame and the reference cube (right foreground) is in the southeast corner of the frame. In Figure 10B region C is seen from the southeast along the northeast side of the fault. The main shock is outside this region, but it was included (disc in the lower distance) for reference. The off-fault earthquakes southwest of the fault appear to be bounded on the southwest by a northeast-dipping plane that intersects the fault at a depth of 8 km or more.

In Figure 10C region S is seen from the northwest along the northeast side of the fault. The principal concentration of off-fault aftershocks is only 2 to 4 km deep and lies directly against the fault on its southwest side. In this plot and in Figure 7C, the northeast edge of this shallow cluster appears to be bounded by a curved surface that dips about 40°SW at its lower end and merges with the main fault (dipping about 80°NE) at its upper end.

DISCUSSION

The Morgan Hill earthquake and its aftershocks are of great importance to our understanding of tectonic processes along and east of the Calaveras and Hayward Faults in central California. They occurred at the southern end of the East Bay Hills (Aydin, 1982) where the Hayward and Calaveras Faults approach each other and where clear examples of other structures characterizing the tectonics of the region are found (Page, 1982a, 1982b). These features include pull-apart valleys (Halls Valley, San Felipe Valley and Coyote Lake) along the Calaveras and high angle reverse faults (Silver Creek and Coyote Creek Faults) that appear to be associated with the Calaveras. Complexities in the aftershock pattern appear to be associated with some of these features.

In comparing the locations of the aftershocks with mapped surface features, we should allow for a possible systematic mislocation of the aftershocks of about 1 km toward the northeast. The occurrence of higher crustal velocities northeast of the fault than southwest of it, as was suggested by the main shock first motion plot, could lead to such a mislocation. The most intriguing feature of the aftershock distribution is the large aftershock-free zone that is surrounded and outlined by aftershocks in the longitudinal sections (Fig. 5B, particularly). We argue that this zone, which contains the main shock hypocenter at its northwest end, represents the area on the fault surface that slipped during the main shock and remained quiet thereafter. The encircling band of aftershocks represents the subsequent extension of the slipped zone on the fault surface. The quiet zone can be divided into two sections on the basis of the depth to its top. The 10 km-long northwest section averages about 3 km in height and extends roughly from 6 to 7 km depth to about 10 km depth. The 13 km-long southeastern section averages about 5 km in height and extends from about 4 km depth to about 10 km depth. The boundary between the two sections is approximately at the change in strike of the central band of aftershocks. Bakun et al. (1984) interpret a prominent late pulse on strong motion records of the main shock as a second, delayed source of the Morgan Hill earthquake. This pulse appears to have originated 5 seconds after and 16 to 20 km southeast of the initial source. In Figure 5 the second source would plot between -7 and -11 km on the distance axis, in the southeast half of the southeast section of the aftershock free zone. Where the aftershock zone bounding the quiet region descends below about 11 km, it disappears. We take that depth to be the base of the seismogenic layer in the region.

The most prominent group of aftershocks outside the central band (Fig. 3) lies southwest of the central band from San Felipe Valley to the southeast end of Anderson Lake. The lower limit of these aftershocks appears to be a NE-dipping surface that would outcrop in the region of the Silver Creek and Coyote Creek Faults, if projected to the earth's surface, and intersects the central band of aftershocks at a depth of 8 to 10 km near the southeast end of San Felipe Valley. These aftershocks are concentrated at depths of 7 to 8 km near the central band just southeast of San Felipe Valley. At the southeast end of Anderson Lake they are concentrated at depths of 2 to 4 km and are immediately adjacent to the central band. From their spatial distribution, these aftershocks suggest that movement on the Silver Creek or nearby related reverse faults either accompanied or was stimulated by the Morgan Hill earthquake.

The mapped strands of the Calaveras Fault step to the right about 2 km as they traverse San Felipe Valley. No such offset is seen in the fault surface

outlined by the central band of aftershocks at this location. However, from the southeast end of San Felipe Valley to the northwest end of Anderson Lake the offset mapped strand of the Calaveras Fault is mimicked by the 7 to 8 km-deep alignment of aftershocks that is offset about 2 km southwest of the central band.

Although the structure of the fault surface suggested by the spatial distribution of aftershocks in the central band is simple when compared with the mapped strands of the fault, there are several important changes along it. These changes include a small but clear change in strike (N35°W to N29°W, from northwest to southeast) about 5 km southeast of San Felipe Valley and a progressive change in dip from the northwest end (88°NE) to the southeast end (81°NE) of the aftershock zone.

A closer examination of the relationship of the aftershocks to the Calaveras Fault and related structures will require the determination of a substantial number of aftershock focal mechanisms.

ACKNOWLEDGEMENTS

We wish to acknowledge the indispensible contributions to this paper that were made by Carl Johnson, Sam Stewart, and Peter Johnson, who developed and implemented the digital data acquisition system and interactive analysis system, and to Shirley Marks, Mike Stephens, and Gail Nishioka, who analyzed the Morgan Hill aftershocks with that system.

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Table 1: Seismic station locations, and delays calculated from Program VELEST, for the stations used in locating the earthquakes reported in this study. The stations labelled 'Temp' were installed to augment the permanent network immediately after the main shock on April 24.

Station	Latitude (North)		Longitude (West)		Delay (seconds)
BAV	36°	38.75'	121°	1.79'	-0.18
BEM	36	39.68	121	5.76	0.15
BHR	36	43.67	121	15.83	-0.02
BHS	36	21.35	121	32.39	-0.44
BJC	36	32.82	121	23.53	-0.36
BJO	36	36.65	121	18.81	-0.20
BPC	36	34.32	121	37.56	-0.09
BSL	36	46.53	121	20.96	0.12
BSR	36	39.99	121	31.12	-0.15
BVY	36	44.96	121	24.80	0.55
CAD	37	9.83	121	37.55	0.39
CAI	37	51.68	122	25.77	-0.52
CAL	37	27.07	121	47.95	0.00
CAO	37	20.96	121	31.96	-0.10
CBS	37	49.06	121	38.43	0.68
CCO	37	15.46	121	40.35	0.41
CCY	37	33.10	122	5.45	-0.32
CDA	37	43.80	121	43.70	-1.03
CDO	37	43.80	121	50.12	0.93
CDV	37	33.98	121	40.81	0.02
CMC	37	46.88	122	10.55	0.05
CMH	37	21.57	121	45.38	0.29
CMJ	37	31.25	121	52.23	0.10
CML	37	28.64	121	39.09	0.12
CMM	37	27.34	121	29.62	-0.01
CMN	37	37.65	121	42.50	0.14
CMO	37	48.68	121	48.15	1.02
CMP	37	21.46	121	18.51	-0.24
CMR	37	35.68	121	38.22	0.00
COS	37	30.51	121	22.44	0.00
CPL	37	38.25	121	57.64	0.09
CRA	37	46.03	121	56.25	1.07
CSA	37	40.42	121	42.25	0.27
CSC	37	17.11	121	46.35	0.68
CSH	37	38.88	122	2.57	0.81
CST	37	38.35	121	29.89	0.39
CVA	37	37.10	121	45.49	0.18
CVL	37	37.58	121	50.14	0.31
HAZ	36	53.08	121	35.45	0.37
HBT	36	51.01	121	33.04	0.46
HCA	37	1.52	121	29.02	0.01
HCB	36	55.86	121	39.63	0.26
HCO	36	53.31	121	42.34	0.39
HCP	37	11.67	121	11.08	-0.20
HCR	36	57.46	121	35.01	-0.01
HDL	36	50.12	121	38.64	0.16
HFE	36	59.00	121	24.09	-0.15
HFH	36	53.29	121	28.13	0.36
HFP	36	45.22	121	29.43	0.24
HGS	37	5.75	121	26.83	-0.15
HGW	37	1.02	121	39.02	0.09
HJG	36	47.88	121	34.43	0.16
HJS	36	48.99	121	17.92	-0.03
HKR	36	54.10	121	25.56	0.42
HLT	36	53.07	121	18.49	-0.19
HMO	36	36.03	121	55.06	-0.29
HOR	36	55.03	121	30.46	0.05

Station	Latitude (North)		Longitude (West)		Delay (seconds)	
HPH	36°	51.38'	121°	24.37'	0.65	
HPL	37	3.13	121	17.40	-0.28	
HPR	36	57.19	121	41.70	0.32	
HQR	36	50.02	121	12.76	-0.25	
HSF	36	48.72	121	29.97	0.74	
HSL	37	1.16	121	5.13	-0.05	
HSP	37	6.91	121	30.94	0.09	
JAL	37	9.50	121	50.82	0.17	
JBC	37	9.62	122	1.57	0.23	
JBG	37	20.52	122	20.34	0.03	
JBL	37	7.67	122	9.98	-0.17	
JBM	37	19.09	122	9.16	0.01	
JBZ	37	1.07	121	49.15	0.46	
JCB	37	6.71	121	41.33	0.16	
JEC	37	3.04	121	48.56	0.23	
JEG	37	30.84	122	27.74	-0.37	
JHL	37	6.56	121	49.95	0.18	
JHP	37	26.65	122	18.09	-0.18	
JLT	37	21.22	122	12.25	-0.06	
JLX	37	12.11	121	59.17	0.03	
JPL	36	58.62	121	49.93	0.56	
JPP	37	15.81	122	12.78	0.13	
JPS	37	11.94	122	20.90	-0.09	
JRG	37	2.22	121	57.86	0.23	
JRR	37	3.27	121	43.61	0.12	
JSA	37	34.95	122	25.03	-0.44	
JSC	37	17.07	122	7.42	0.01	
JSF	37	24.31	122	10.55	-0.02	
JSG	37	16.96	122	3.00	0.52	
JSJ	37	20.03	122	5.48	0.42	
JSM	37	12.74	122	10.06	0.14	
JSS	37	10.17	121	55.84	0.09	
JST	37	12.41	121	47.84	0.22	
JTG	37	1.71	121	52.58	0.46	
JUC	37	0.07	122	2.91	0.02	
AMSG	37	9.60	121	36.90	0.41	Temp
BBLG	37	18.78	121	39.40	0.07	Temp
COEG	37	16.84	121	40.40	0.35	Temp
DFLG	37	17.35	121	37.35	-0.02	Temp
GRTG	37	19.90	121	43.11	0.20	Temp
UTSG	37	12.70	121	39.72	0.74	Temp
LASG	37	14.84	121	40.41	0.62	Temp
LONG	37	11.43	121	37.24	0.57	Temp
NBRG	37	10.17	121	38.76	0.45	Temp
OCRG	37	12.60	121	38.18	0.53	Temp
PHRG	37	18.88	121	41.67	0.17	Temp
RBHG	37	14.07	121	41.13	0.71	Temp
RSTG	37	19.41	121	40.13	0.04	Temp
SFLG	37	14.01	121	34.89	0.09	Temp
SFRG	37	16.96	121	44.32	0.67	Temp
ECL	37	7.12	121	33.14	0.27	Temp
ECP	37	11.18	121	33.01	0.09	Temp
ECW	37	17.46	121	27.75	-0.13	Temp
ELA	37	13.16	121	39.28	0.54	Temp
EMK	37	23.00	121	40.17	-0.08	Temp
ESC	37	19.35	121	40.12	-0.02	Temp

Table 2. P-wave velocity model used in this study. Vp is the velocity in km/s and Z is the depth in km to the top of the layer.

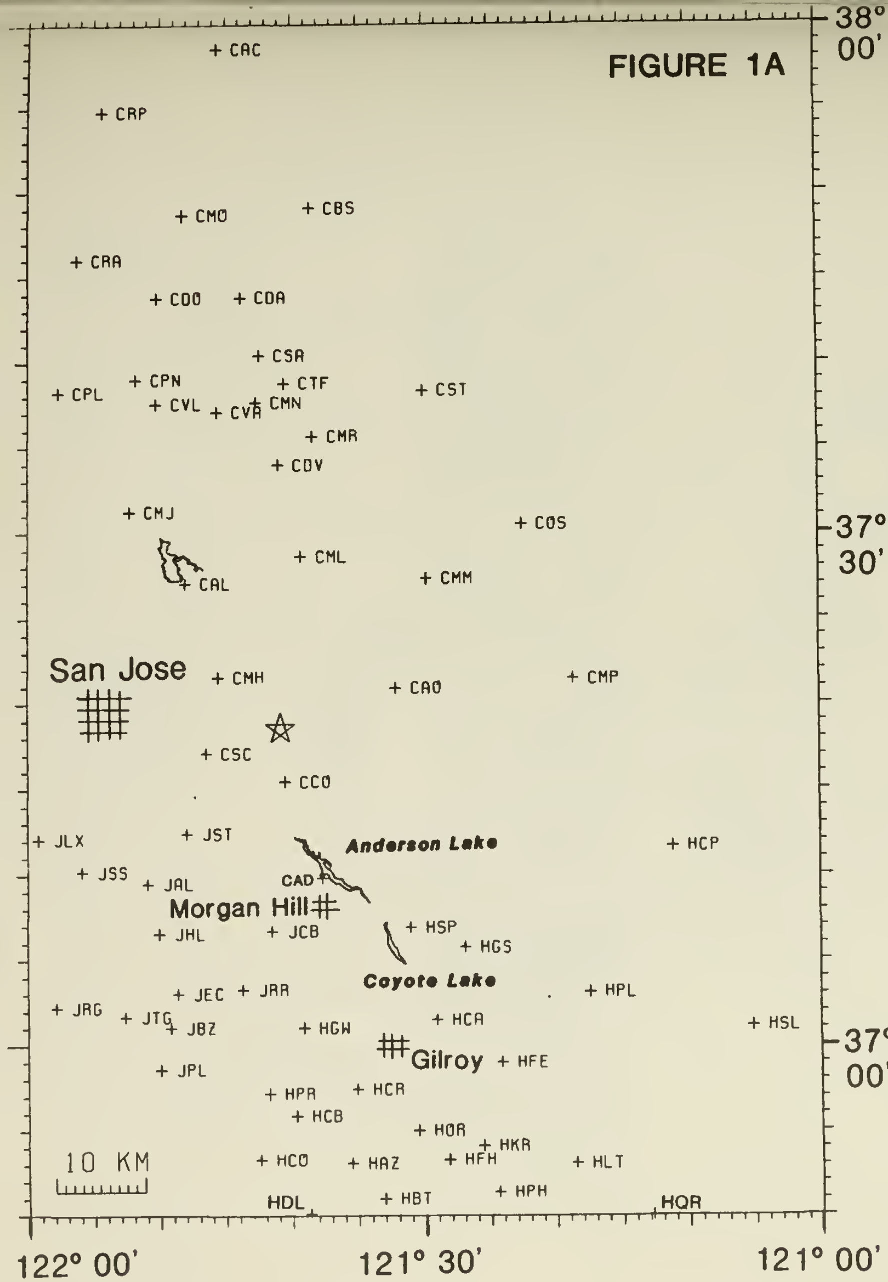
Vp	Z
3.67	0.0
4.80	0.5
5.27	2.0
5.76	4.2
6.05	10.0
6.20	14.0
7.60	25.0

Table 3: Magnitude determinations for the main shock

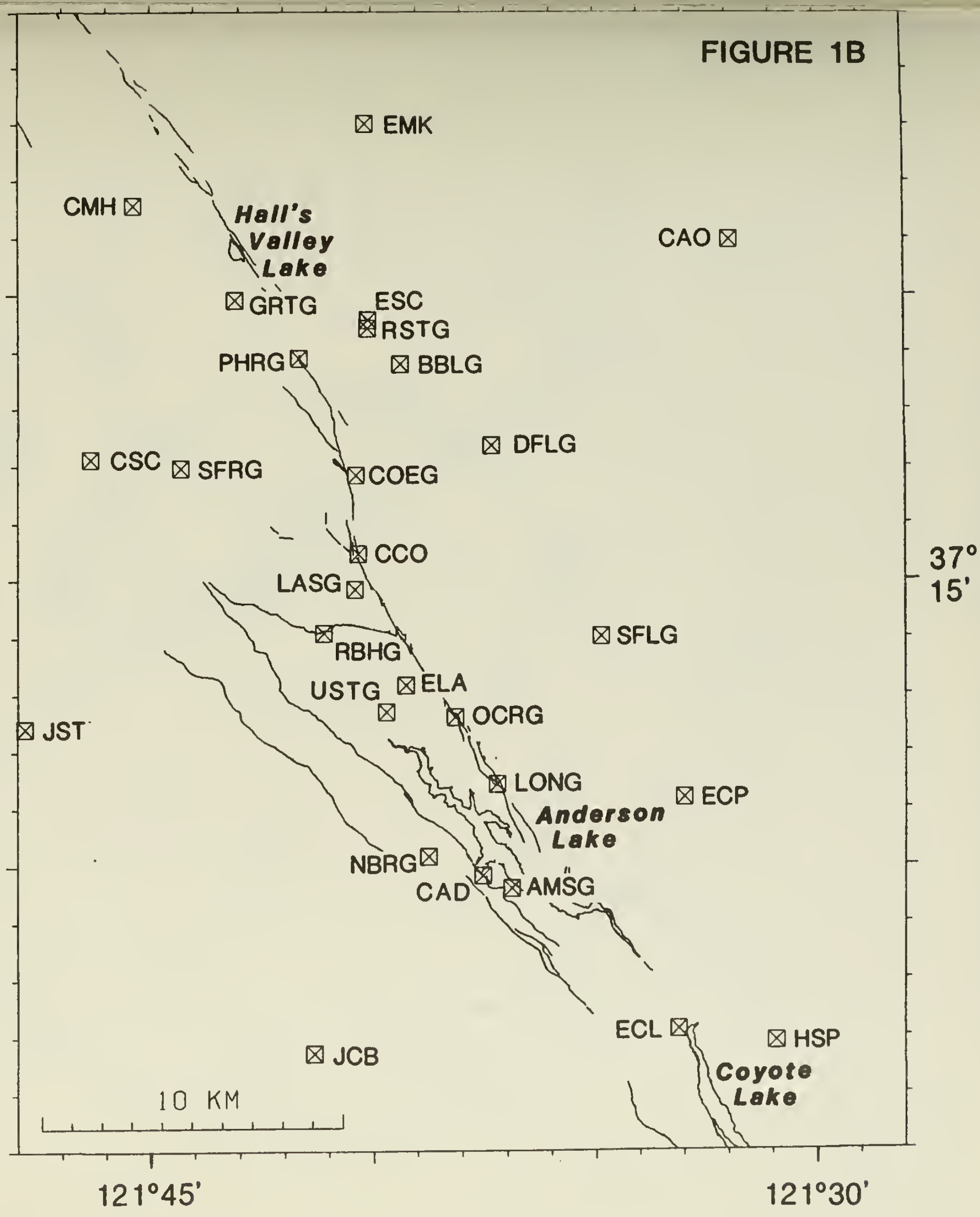
Station	Distance	Azimuth	Magnitude M_L
LTCN	324 km	353 deg	6.2
KMPN	405	328	6.0
KMPE	405	328	6.3
RLBZ	459	131	6.7
RBRZ	481	132	6.6
RGAZ	525	134	6.4
RBIZ	548	127	7.0
RRFZ	571	129	7.0
RPBZ	590	133	6.5
DCUZ	607	125	6.8
REWZ	609	128	6.9
ECYZ	656	132	6.8
ICWZ	663	127	6.7

No. Cal. average = 6.17

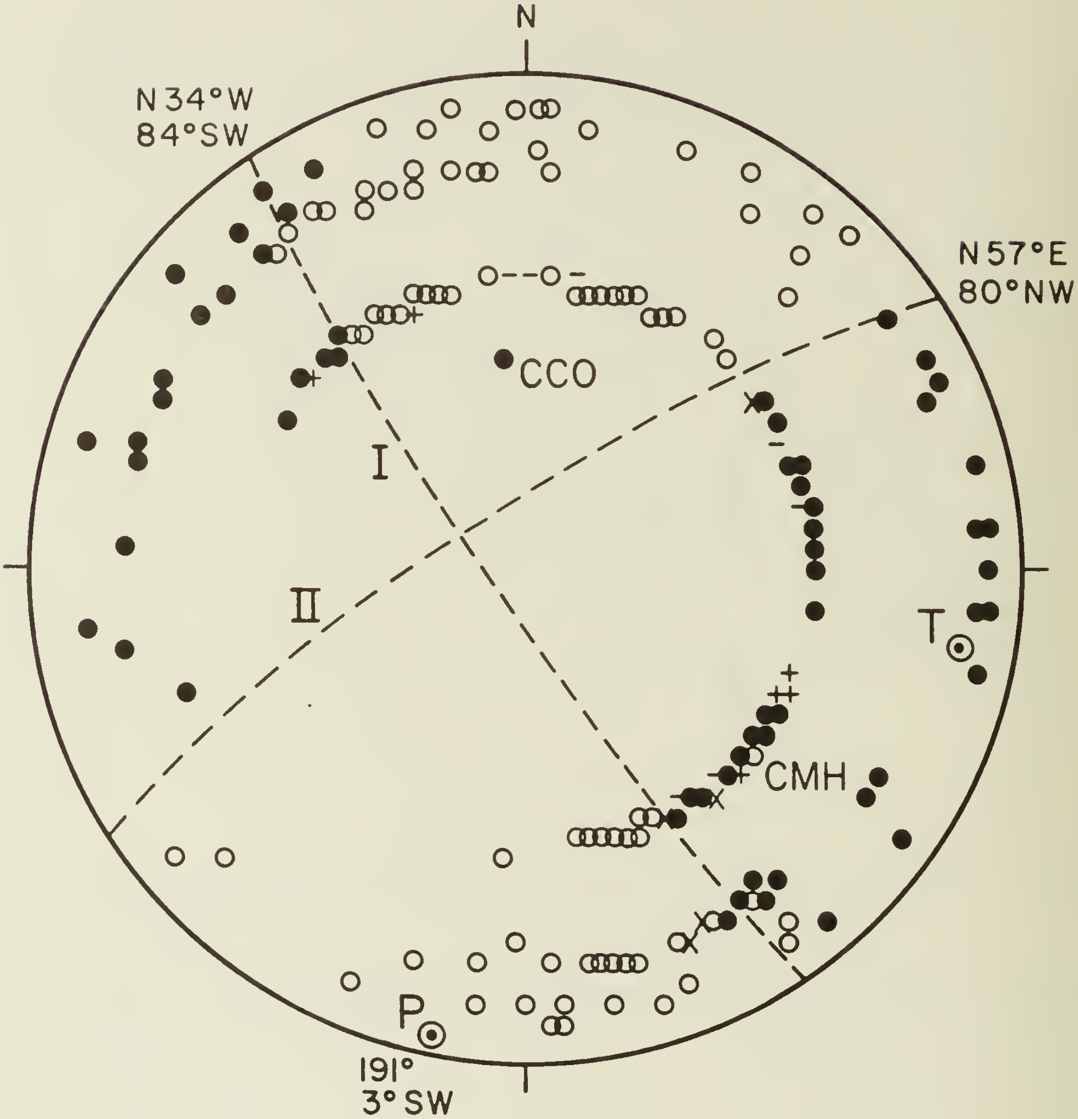
So. Cal. average = 6.74 -(0.00 to 0.25) = 6.5 to 6.7



(A) Map showing the epicenter of the Morgan Hill earthquake (star), stations of the northern California telmetered seismic net (crosses, with 3-letter station codes), and physiographic features mentioned in the text.



(B) Map showing the strands of the Calaveras Fault and nearby reverse faults (Herd, 1982), physiographic features mentioned in the text, and the augmented seismic net used to study the Morgan Hill aftershocks (square symbols).



First motion plot and focal plane solution for the main shock. The plot is an equal area projection of first motions on the lower hemisphere. Closed circles and +'s represent certain and questionable compressional first arrivals. Open circles and -'s represent certain and questionable dilatational first arrivals. X's represent conflicting first arrivals. P and T denote the inferred axes of maximum and minimum compression, respectively.

FIGURE 2

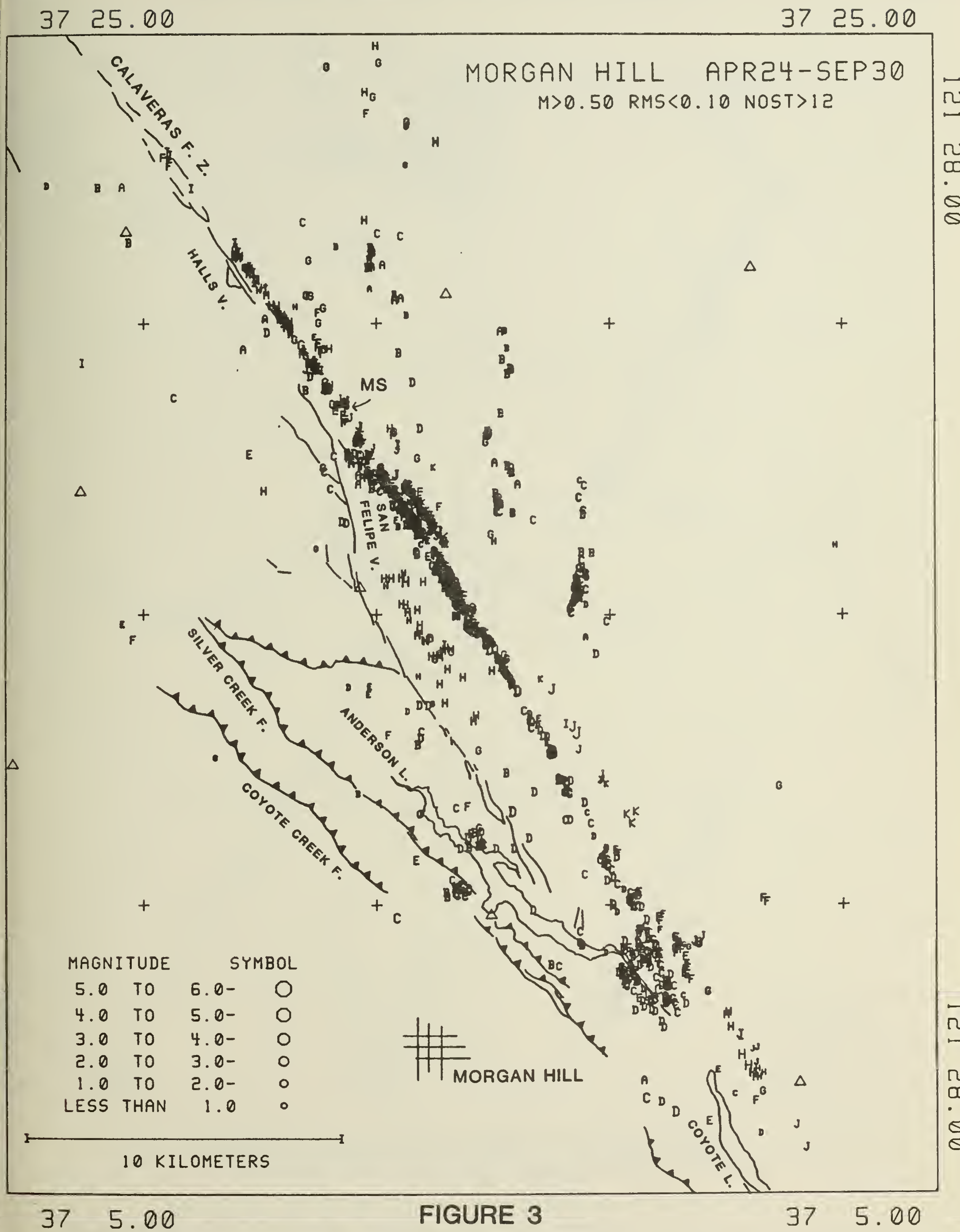


FIGURE 3

Map of the epicenters of the Morgan Hill earthquake of April 24, 1984 and its aftershocks through Septermber 30, 1984. Magnitudes and focal depths are indicated by symbol size and letter: A, $0<H\leq 1$; B, $1<H\leq 2$, ... ; K, $10<H\leq 11$km. Fault traces are from Herd (1982). Triangles are seismic stations of the permanent network.

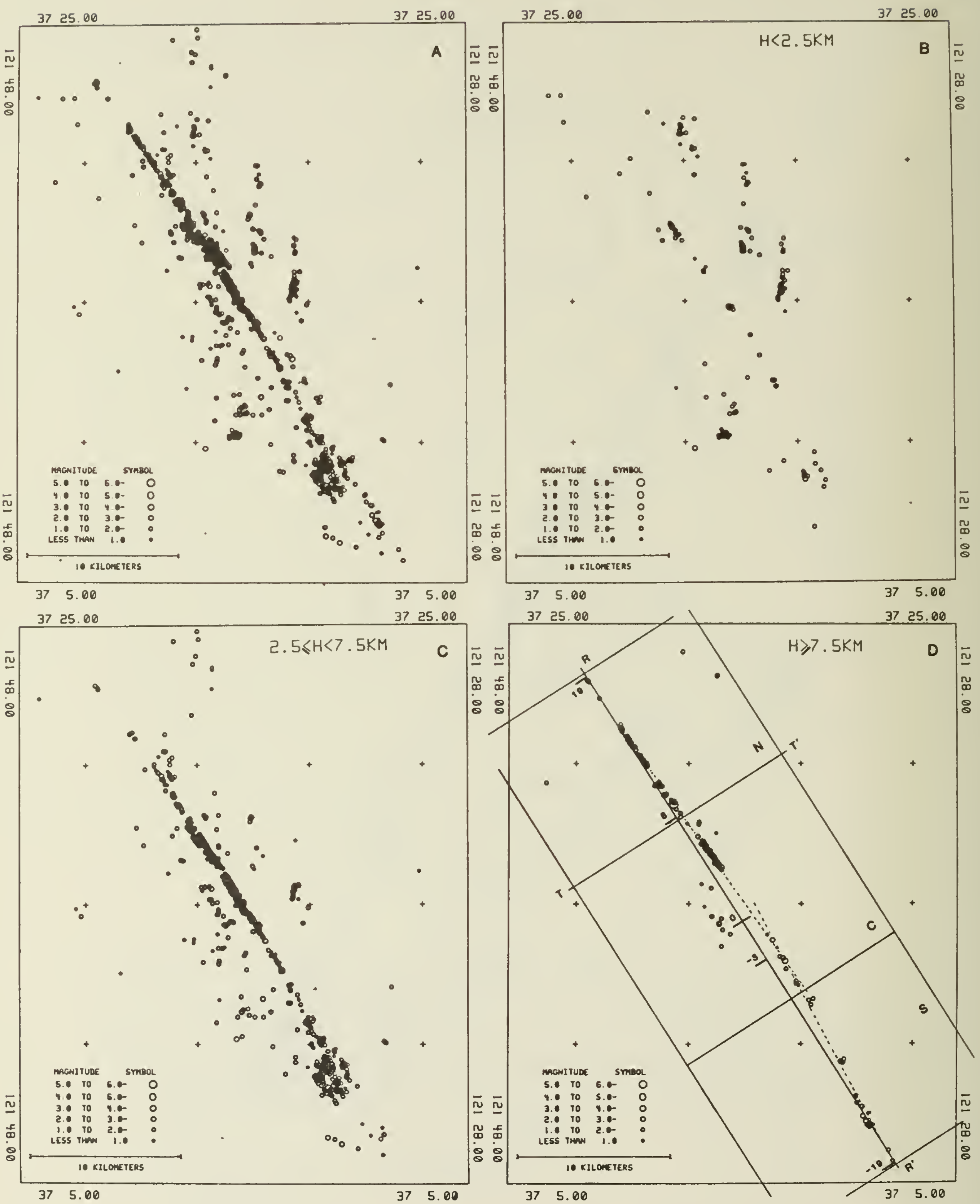


FIGURE 4 Maps showing the aftershock pattern as a function of focal depth range: A, H > 0km; B, H ≤ 2.5km; C, 2.5km ≤ H ≤ 7.5km; D, H ≥ 7.5km. The lines R-R' and T-T' are longitudinal and transverse section lines. The frames N, C, and S are subregions for which separate plots are constructed.

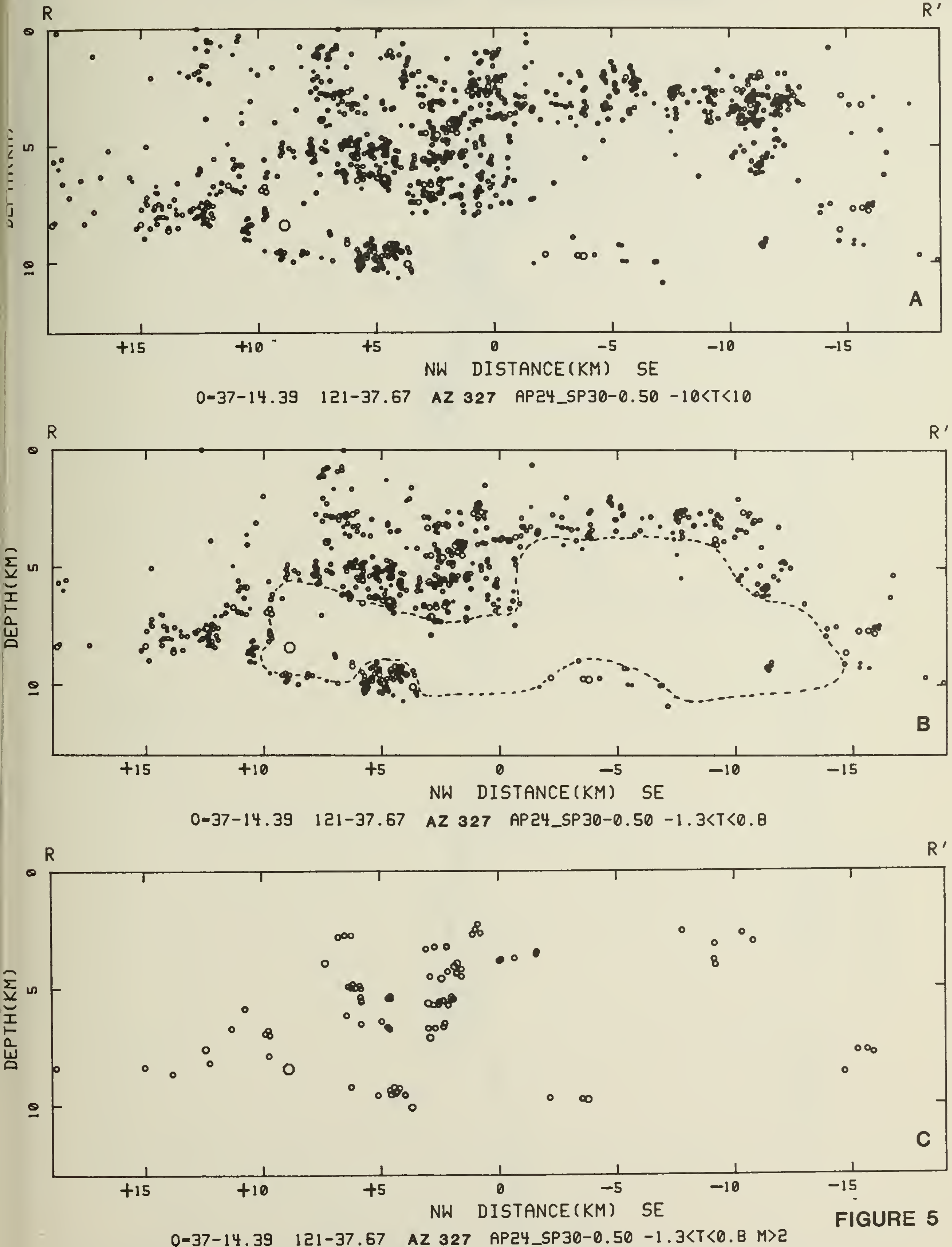


FIGURE 5

Longitudinal sections of the aftershock distribution along line R-R' (Fig. 4D). In section A, all events within 10 km of R-R' are included in the plot. In sections B and C, only events within 1.3 km northeast and 0.8 km southwest of R-R' are included in the plot. In section C, only events with M $\geqslant$2.0 are plotted.

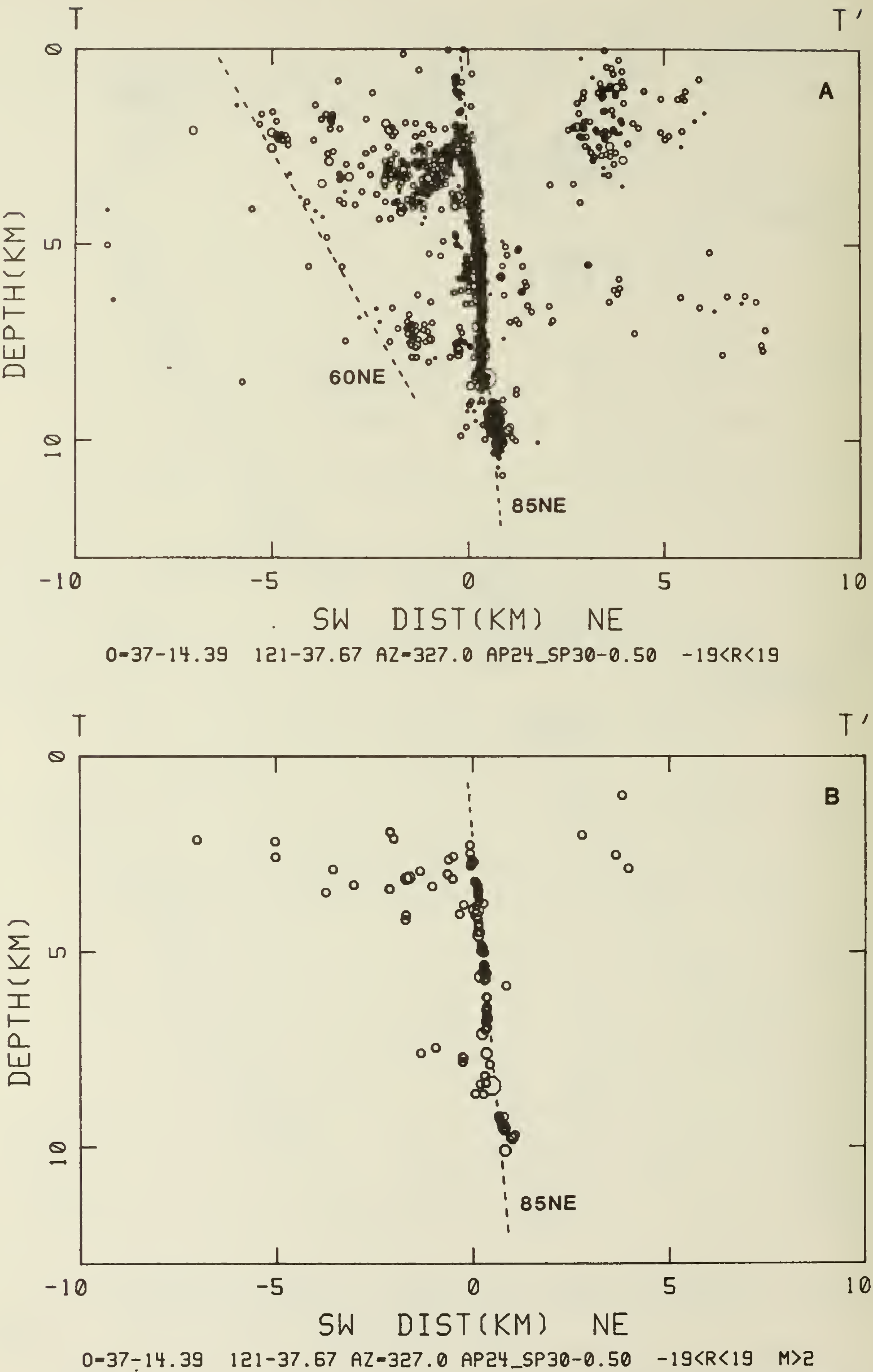


FIGURE 6 Transverse sections of the aftershock distribution along the line T-T' of all events between R and R' (Fig. 4D). In section A all events are included. In section B only events with M ⩾2.0 are included.

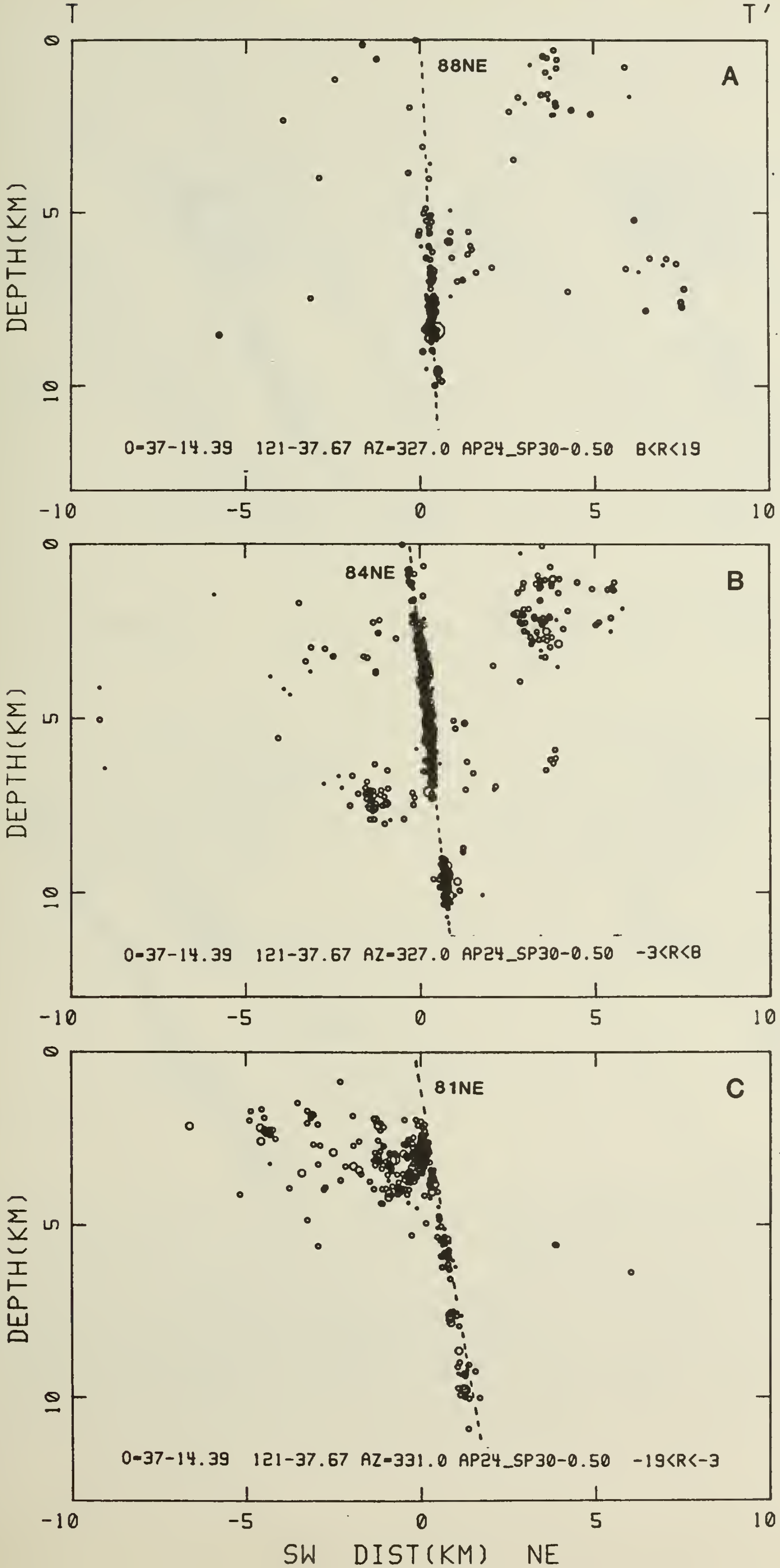


FIGURE 7

Transverse sections of aftershocks in frames N,C and S (Fig. 4D). Sections N and C are perpendicular to an azimuth of 327° (R-R', Fig.4D). Section C is perpendicular to an azimuth of 331°.

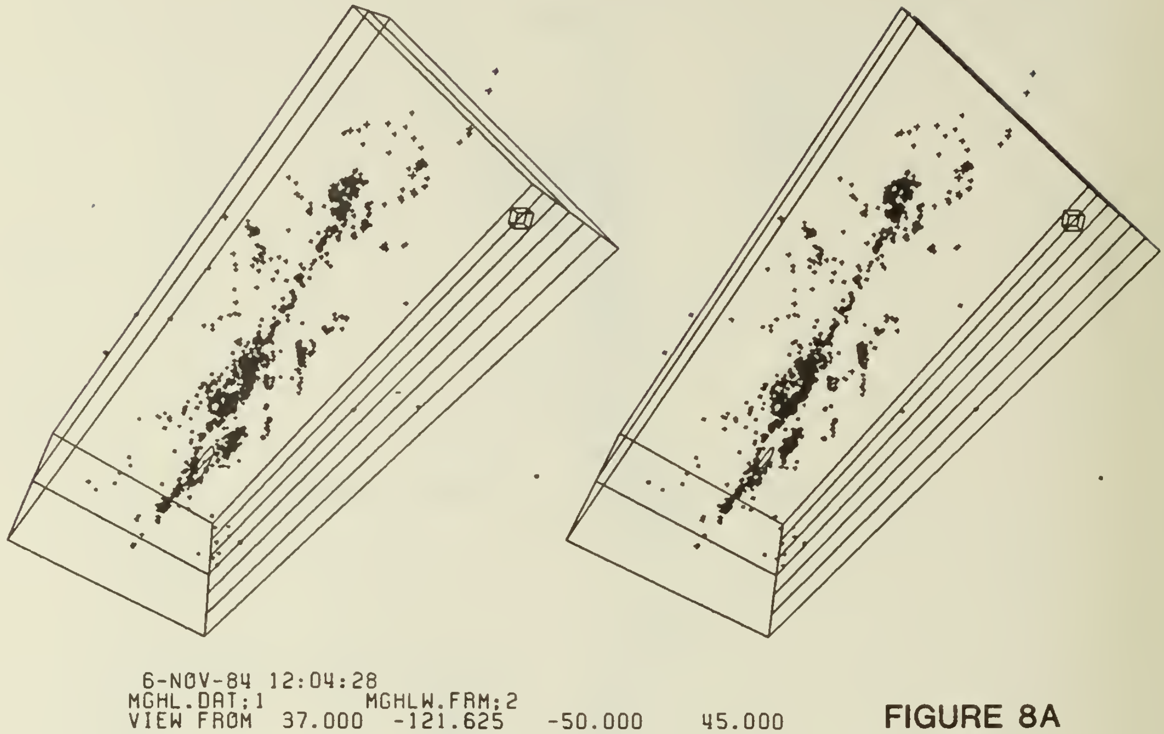


FIGURE 8A

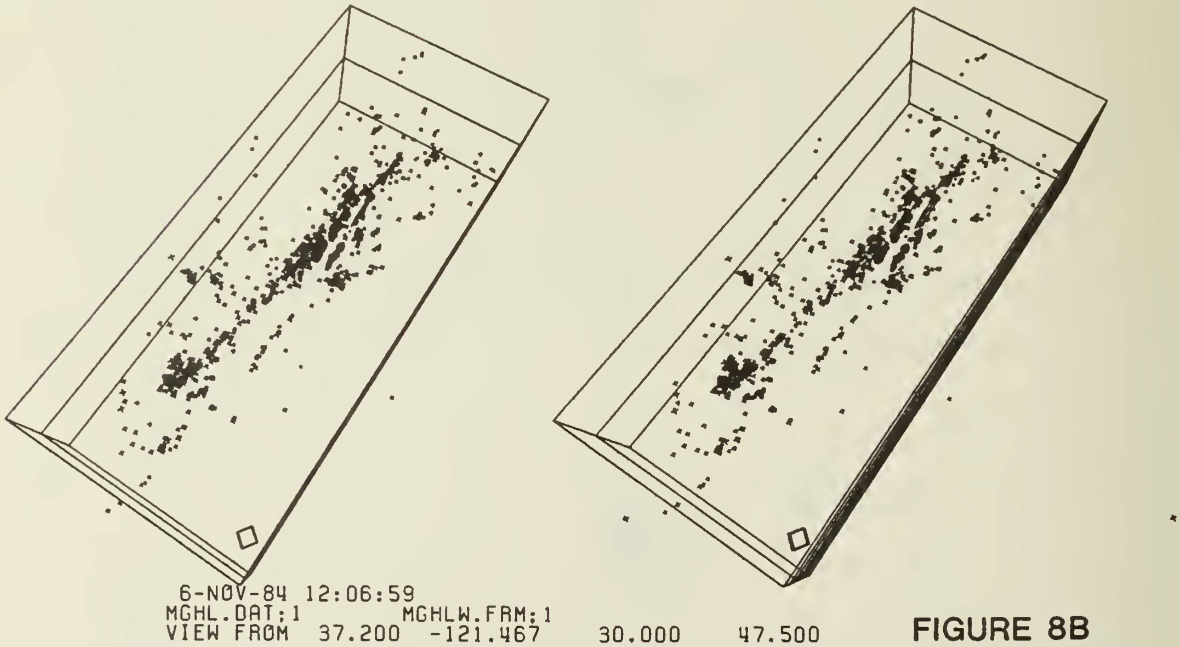
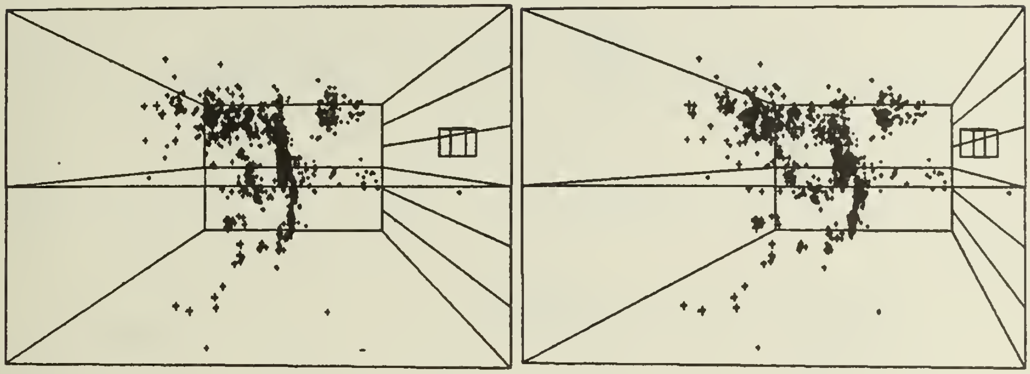


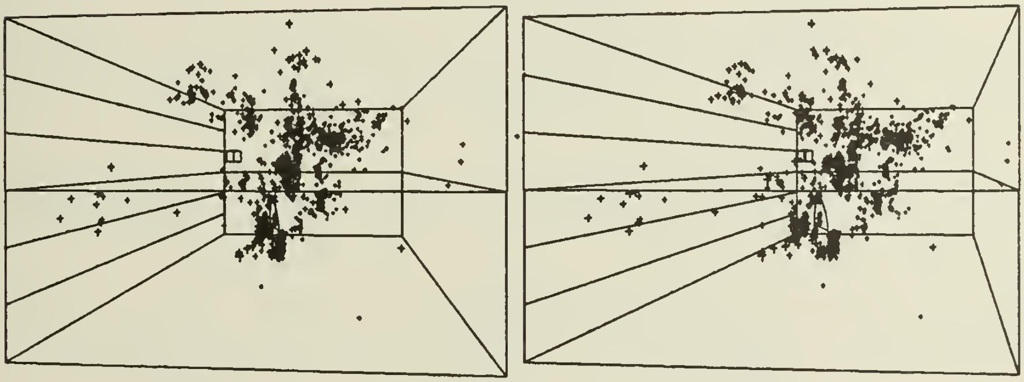
FIGURE 8B

Stereo-pair plots of the Morgan Hill earthquake and its aftershocks from below (A) and from above (B). In A the viewing point is 50 km deep and approximately beneath the southwest corner of the frame. In B the viewing point is 30 km above the earth and approximately above the southeast corner of the frame. In both plots the frame is the combined region N,C and S in Fig. 4D. It is 12 km in height and has 2-km intervals marked on one face. A 1-km reference cube with its horizontal edges oriented N-S and E-W is shown in the southeast corner of both frames. The main shock is plotted as a circle lying in the fault plane deduced from the focal plane solution. The aftershocks are plotted as +'s and are scaled weakly according to magnitude.



10-NOV-84 08:37:07
MGHL.DAT;1 MGHLW.FRM;4
VIEW FROM 37.080 -121.450 -5.000 41.000

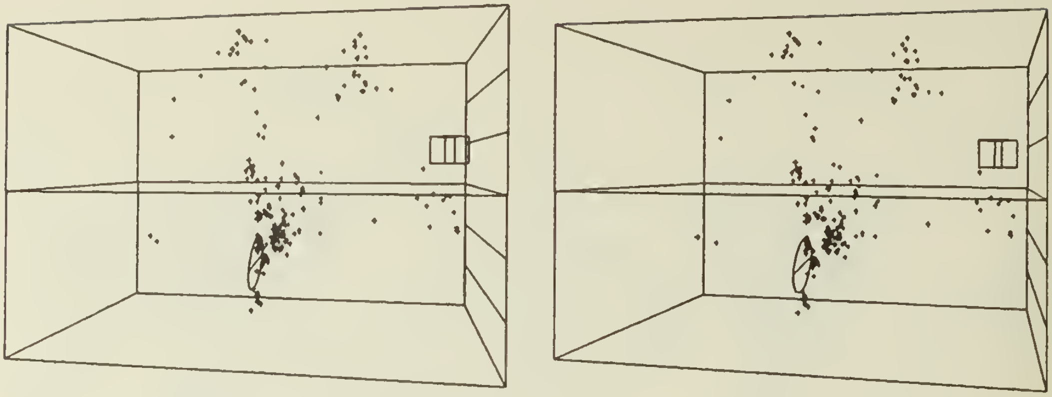
FIGURE 9A



10-NOV-84 08:35:20
MGHL.DAT;1 MGHLW.FRM;6
VIEW FROM 37.400 -121.800 -5.000 41.000

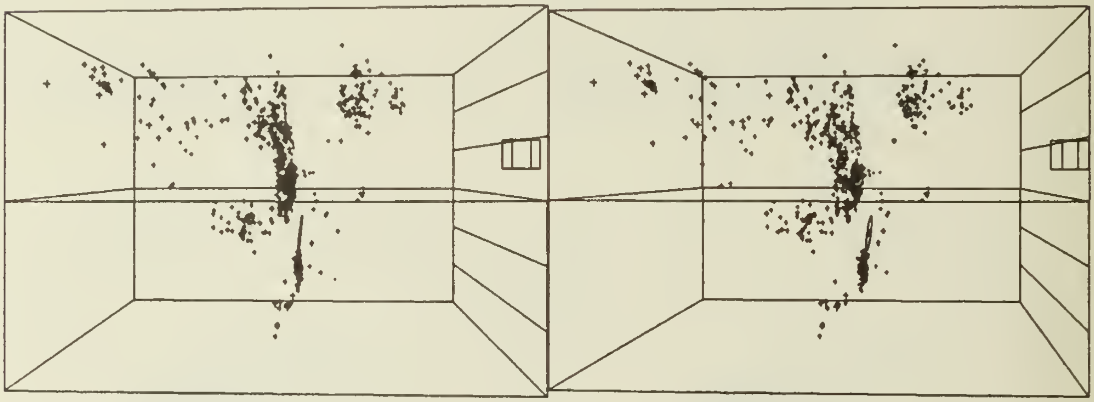
FIGURE 9B

Stereo-pair plots of the Morgan Hill earthquake and its aftershocks from the southeast (A) and from the northwest (B). The main shock is plotted as a circle lying in the fault plane and with a diameter-line showing the direction of slip. Aftershocks are plotted as +'s and are scaled weakly according to magnitude. In A the viewing point is 5 km deep and the line of sight is toward the northwest along the northeast side of the fault surface. In B the viewing point is 5 km deep and the line of sight is southeast along the southwest side of the fault surface. In both plots the frame is the combined region N,C and S (Fig. 4D). It is 12 km in height and has 2-km intervals marked on one face. A 1-km reference cube with its edges oriented N-S and E-W is shown in the southeast corner of each frame.



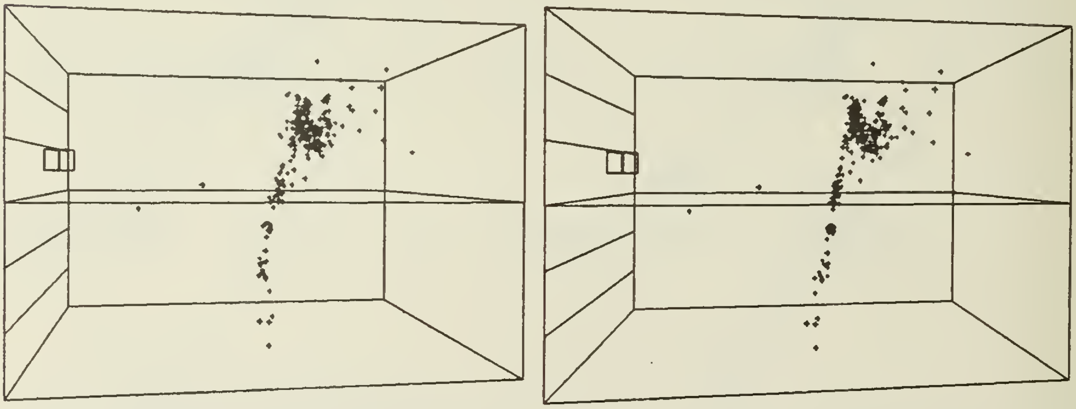
6-NOV-84 12:12:43
MGHLNR.DAT:1 MGHLN.FRM:1
VIEW FROM 37.302 -121.650 -5.000 27.000

FIGURE 10A



6-NOV-84 12:14:10
MGHLCR.DAT:1 MGHLC.FRM:2
VIEW FROM 37 0 -121.520 -5.000 27.000

FIGURE 10B



6-NOV-84 12:14:57
MGHLSR.DAT;1 MGHLS.FRM;2
VIEW FROM 37.252 -121.610 -5.000 27.000

FIGURE 10C

Stereo-pair plots of events in regions N,C and S (plots A, B, and C, respectively) of Figure 4D. The main shock is plotted as a circle lying in the fault plane and with a diameter-line showing the direction of slip. The aftershocks are plotted as +'s and are scaled weakly according to magnitude. The frames, which correspond to the regions N,C and S in Figure 4D, are all 12 km in height and have 2-km intervals marked on one face. In A the viewing point is 5 km deep and the line of sight is toward the northwest along the northeast side of the fault. In B the viewing point is 5 km deep and the line of sight is toward the northwest along the northeast side of the fault. In C the viewing point is 5 km deep and the line of sight is toward the southeast along the northeast side of the fault. A 1-km reference cube with its edges oriented N-S and E-W is shown in the southeast corner of each frame.

HISTORY OF EARTHQUAKE DAMAGE IN SANTA CLARA COUNTY

and

COMPARISON OF 1911 AND 1984 EARTHQUAKES

by

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ABSTRACT

Earthquake damage in Santa Clara County has occurred 21 times in the 130 years of available written records. It occurred most frequently in the decades preceding the large earthquakes of 1868 and 1906. The 1984 earthquake on the Calaveras fault was centered near the 1911 earthquake, and had about the same magnitude. The 1984 earthquake was more strongly felt south of Morgan Hill, and the 1911 earthquake was more strongly felt to the north.

INTRODUCTION

The history of earthquake damage in Santa Clara County is complete back to the 1850's, when newspapers were established in the San Francisco Bay area. This history is summarized in Table 1.

The two largest and most destructive earthquakes to affect Santa Clara County are the 1868 earthquake that occurred on the Hayward fault, and the 1906 earthquake that occurred on the San Andreas fault. Earthquake damage in Santa Clara County occurred five times in the decade preceding the 1868 earthquake, and four times in the decade preceding the 1906 earthquake. In addition, on 15 April 1898 a magnitude 6.4 earthquake (Toppozada et al., 1981) was destructive on the coast of Mendocino County, near the northern part of the San Andreas fault that was to rupture in 1906.

Thus damaging earthquakes occurred most frequently in the decades leading up to the two largest historical earthquakes in the San Francisco Bay area, and most of these earthquakes were damaging in Santa Clara County. Conversely, earthquake damage in Santa Clara County occurred least frequently in the decades following the two largest earthquakes in the Bay area. Following the 1868 earthquake, only two earthquakes occurred in two decades, and following the 1906 earthquake, only three earthquakes occurred in seven decades. The seismic quiescence following the 1906 earthquake extended to the north of the Bay area, where the largest earthquake (magnitude 5.7) occurred in 1969 in Sonoma County.

These observations suggest that in the Bay area, earthquakes of magnitude about 6 occur more frequently as the regional stress builds up to the level required for larger earthquakes (magnitude about 7 or larger).

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Table 1. Earthquakes Causing Damage in Santa Clara County Since 1850.

Date	Magnitude	Damage[x]
1858/11/26	6.1*	At San Jose, brick walls were cracked and chimneys were thrown down. At San Francisco, a cornice was thrown down and a number of buildings were cracked.
1864/02/26	5.9*	At San Jose and Monterey, deep sleepers awoke (5.47 a.m.) and cracks in buildings widened. At San Francisco, glass was broken and a bookcase was knocked over.
1864/03/05	5.7*	At San Jose, plastering was slightly damaged. At San Francisco, windows and plastering broke, and buildings cracked.
1865/10/08	6.3*	At San Jose, some brick walls and several chimneys were thrown down. At San Francisco, several walls collapsed. Ground cracking near the San Andreas fault in the Santa Cruz Mountains may have been faulting.
1866/03/26	5.4*	At Gilroy, several chimneys tumbled down. At San Francisco, plaster cracked and a few panes of glass broke.
1868/10/21	6.8*	The Hayward earthquake: At San Jose, chimneys, church turrets, and a water tower fell. Damage of similar intensity occurred in San Francisco, and throughout coastal Alameda County where the Hayward fault ruptured over a length of 50 km.
1870/02/17	5.8*	Centered near the San Andreas fault between Los Gatos, where chimneys fell, and Santa Cruz, where walls cracked and chimneys were dislocated.
1883/03/30	5.6*	Centered near the San Andreas fault between Gilroy, where walls were cracked and a chimney or two fell, and Watsonville, where considerable plastering fell.
1890/04/30	6.0*	Apparent faulting on the San Andreas fault between Sargents (southwesternmost Santa Clara County), where chimneys and an adobe fell, and Watsonville, where plaster broke and heavy articles moved.
1891/01/02	5.5*	Plastering was shaken down at Mount Hamilton and at Santa Cruz.
1897/06/20	6.2*	Chimneys were down at Gilroy and at Watsonville.
1898/03/31	6.2*	Centered in the north bay area, near the juncture of Solano, Napa, and Sonoma counties. At Mare Island, several buildings collapsed. At San Jose, pictures fell and walls cracked slightly.
1903/06/11	5.8+	Tops of chimneys fell at San Jose and at Santa Clara.
1903/08/03	5.8+	Chimneys broke and fell at San Jose and at Santa Clara.
1906/04/18	7.8+	The great San Francisco Earthquake: At San Jose, nearly all the chimneys fell, and buildings fell off their foundations. Damage of similar intensity occurred within 70 km of the San Andreas fault rupture (400 km) from San Benito County to Humboldt County.
1911/07/01	6.2+	Chimneys down at Morgan Hill and Santa Clara. See Table 2 for other damage reports, and Figure 1 for the areal extent of damage.
1955/09/05	5.4	Chimneys fell in San Jose.
1957/03/22	5.3	At San Francisco, some chimneys were damaged and plaster fell. At San Jose, some plaster fell.
1979/08/06	5.8	At Gilroy, five buildings reported some structural damage and many old chimneys were damaged.
1980/01/24	5.8	At Livermore, chimneys were damaged and mobile homes were knocked off their supports. At San Jose, some windows were broken.
1984/04/24	6.2	Chimneys fell at Morgan Hill and Coyote. See Table 2 for other damage reports, and Figure 2 for the areal distribution of damage.

x Figure 1 includes the locations described in this table.
* Magnitude estimated from isoseismal areas by Toppozada et al. (1981).
+ Magnitude estimated from isoseismal areas by Toppozada and Parke (1982).

It is these larger earthquakes, such as those of 1868 and 1906, that release substantial stress and are followed by decades of seismic quiescence. The occurrence of three earthquakes of magnitude 5.8 or larger since 1979 suggests that the area is emerging from the post-1906 quiescence. It is tempting to compare the current increased seismicity to that in the 1860's. However, the short history available does not guarantee that we are now in the decade preceding an earthquake of about magnitude 7 or larger. It is not known if before 1850, earthquakes of about magnitude 6 occurred frequently without presaging a larger earthquake. Moreover, there are sketchy reports of large earthquakes in 1836 and 1838, but their magnitudes are uncertain, and it is unknown how they would fit into a cycle of stress buildup and release. If the 1836 and 1838 earthquakes were in the magnitude 6 range, then they did not presage a large earthquake. Conversely, if they were in the magnitude 7 range, then the occurrence of these larger earthquakes would have extended from 1836 to 1906, and the level of seismicity in the preceding decades is unknown.

COMPARISON OF THE MORGAN HILL EARTHQUAKES OF 1911 AND 1984

The July 1911 earthquake centered southwest of Mount Hamilton, was significantly damaging from Morgan Hill to Santa Clara. This is very similar to the April 1984 earthquake which was also centered southwest of Mount Hamilton, and was significantly damaging from Morgan Hill to Coyote. The damage and felt effects of these two earthquakes are compared to determine their relative locations and magnitudes.

Felt effects at various locations for the 1911 earthquake were determined from the local newspapers and from an article in the Bulletin of the Seismological Society of America (Anon, 1911). This information was obtained in a previous study of California earthquakes (Toppozada et al., 1982) but was thoroughly reviewed and re-evaluated for the present comparison. Felt effects for the 1984 earthquake were determined from USGS questionnaires as well as from newspaper reports.

In order to compare the 1911 and the 1984 earthquakes, the effects of the two events were compared at the same reporting locations. Table 2 lists the effects reported for both earthquakes. The list is arranged alphabetically by county and then alphabetically by town. The effects reported for the 1911 earthquake are listed in the left column and for the 1984 earthquake in the right column.

A value of intensity was assigned based on the reported effects and the Modified Mercalli intensity scale (Wood and Neuman, 1931). Single-word reports, such as "felt", were not used to assign numerical values of intensity; instead, a letter was assigned indicating the earthquake was felt.

A difficulty in comparing the effects in 1911 to those in 1984 is that the USGS questionnaires do not address whether or not the earthquake caused people to run out of buildings. This criterion was useful in determining less than damaging intensities from nineteenth century and early twentieth century newspaper reports. In the absence of noteworthy damage, newspapers would report people running out of buildings. The equivalent criterion, using the USGS questionnaires, is whether or not small objects fell from shelves.

For most of the communities that reported the 1911 earthquake, reports of the 1984 earthquake were available. Reports of the 1911 earthquake are listed even if no report is available for the 1984 earthquake at the same communities. The 1984 earthquake reports are listed for a few communities for which no 1911 reports are available. These communities were selected to add detail to the areal distribution of intensities for the 1984 earthquake, shown in Figure 2. Figure 2 is based largely on U.S. Geological Survey questionnaires, that were used in making Stover's isoseismal map (this volume). The detail in Figure 2 was purposely limited to compare to the limited reports available for the 1911 earthquake (Figure 1).

Figures 1 and 2 are isoseismal maps showing the areal distribution of damage for the 1911 and the 1984 earthquakes. On each map, the outer contour encloses the area shaken at Intensity 6 or greater and is the outside limit of the area having significant damage to glass, china, and plastering. The inner contour on each map encloses the area shaken at Intensity 7, which is the area of downed chimneys and significant damage to walls and foundations.

The greatest damage in 1911 was at Coyote. The greatest damage in 1984 was at Morgan Hill. Surface faulting on the Calaveras fault was minor and equivocal in the 1984 earthquake (Hart, this volume; Galehouse and Brown, 1984; Harms et al., this volume) and was not identified in the 1911 earthquake (Templeton, 1911). Foreshocks that may have given advance warning of a damaging earthquake were absent in the days preceding the 1911 event (Wood, 1912) and in the days preceding the 1984 event (Bakun et al., 1984).

The 1911 earthquake appears to have been more strongly felt to the north than the 1984 earthquake, especially at Antioch, Stockton, and Sacramento (Figures 1 and 2 and Table 2). Conversely, the 1984 earthquake appears to have been more strongly felt to the south than the 1911 earthquake, especially at San Martin and Salinas.

Although the outer contour in Figure 1 is poorly defined, the size of the areas damaged in both earthquakes is nearly the same. In relating magnitude to area, Toppozada (1975) has shown that a factor of two difference in the areas damaged corresponds to only a 1/4 unit difference in magnitude. Because the areas damaged in 1911 and 1984 are about the same size, the local magnitude of the 1911 earthquake appears to be the same as that of the 1984 earthquake, $M_L 6.2$. The published surface-wave magnitude of the 1911 earthquake is $M_S 6.6$.

Both the 1911 and 1984 earthquakes apparently occurred on overlapping segments of the Calaveras fault between Morgan Hill and Mount Hamilton. Their damaging effects were not unprecedented in the South San Francisco Bay Area, which includes the San Andreas fault on the west side as well as the Hayward and Calaveras faults on the east side.

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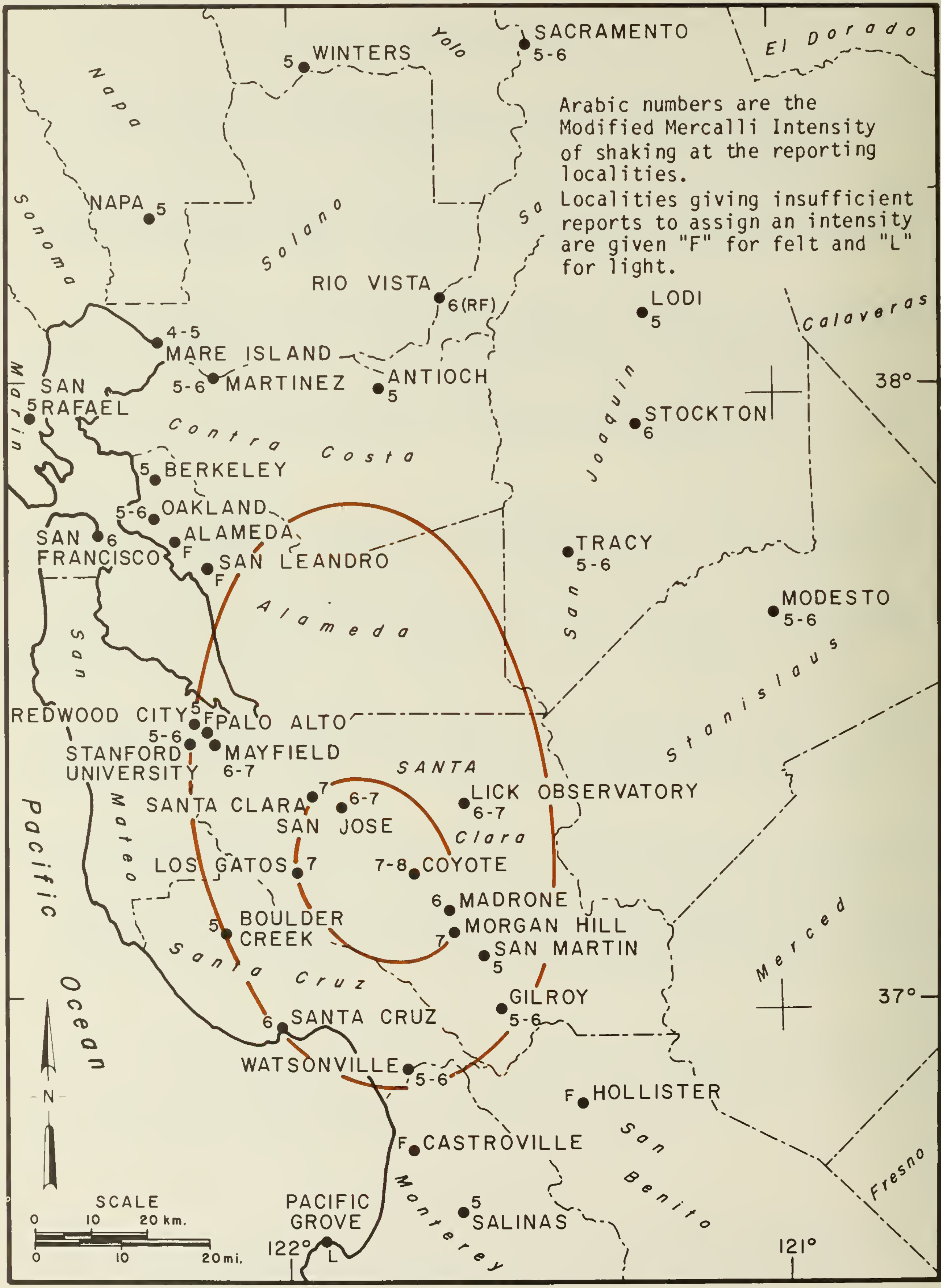

Figure 1. Isoseismal map of 1 July 1911 earthquake. The smoothed isoseismal lines outline the area of minor damage (outer contour) and significant damage (inner contour).

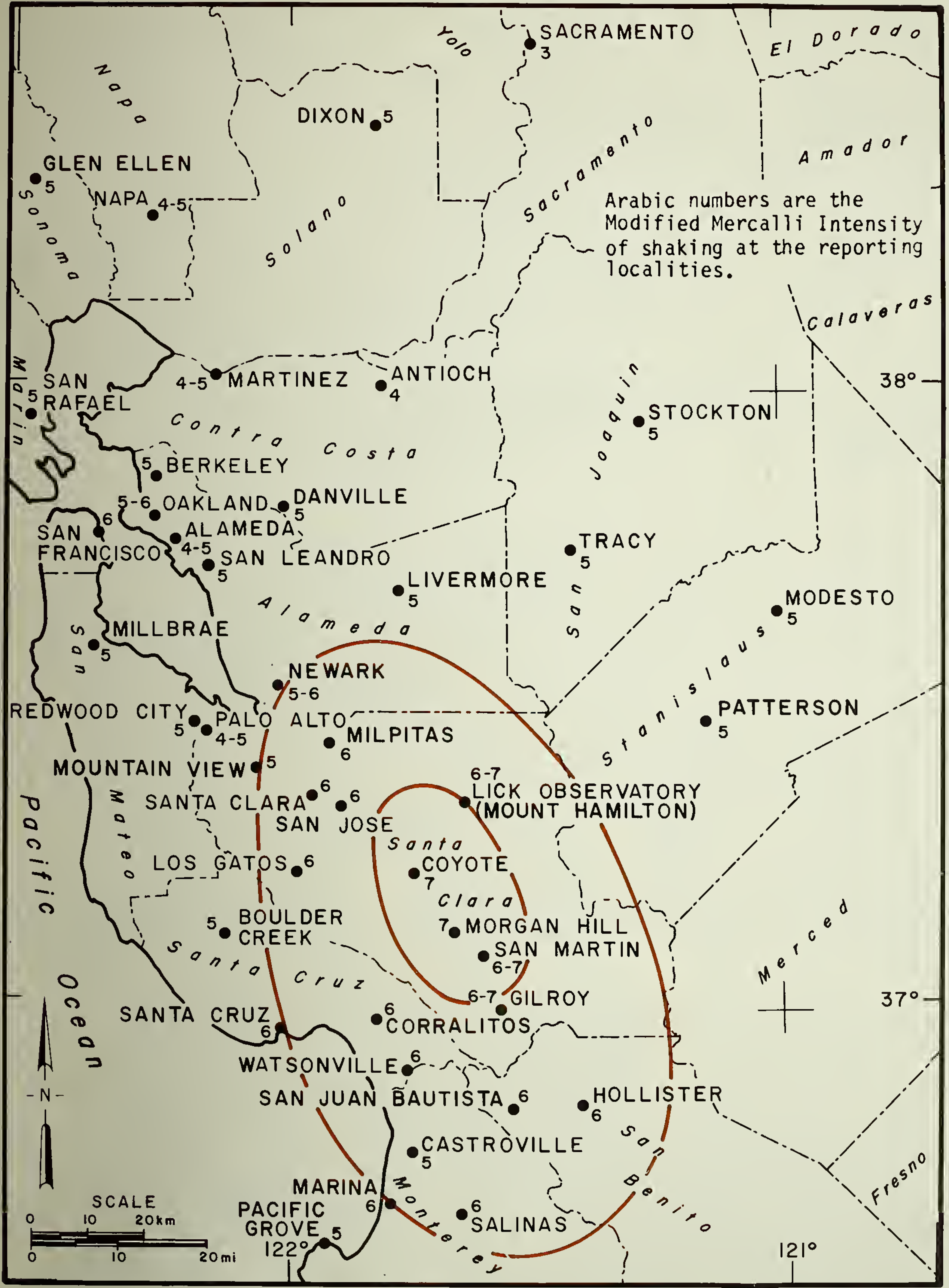

Figure 2. Isoseismal map of 24 April 1984 earthquake. The smoothed isoseismal lines outline the area of minor damage (outer contour) and significant damage (inner contour).

Table 2. Comparison of Reported Effects for 1911 and 1984 Earthquakes.

	1911	1984
	DATE: 1911 Jul 1 TIME: 22:00 GMT EPICENTER: 37.250N 121.750W (BRK)	DATE: 1984 April 24 TIME: 21:15 GMT EPICENTER: 37.32N 121.68W (BRK)
ALAMEDA COUNTY		
Alameda	I = F Felt. The San Francisco Examiner, 2 July 1911, p. 67.	I = 4-5 Felt by all and frightened many. (at work). USGS(questionnaires).
Berkeley	I = 5 There was the usual exodus from tall buildings into the street. No damage was done." Oakland Tribune, 1 July 1911, p. 1. Furniture was shaken and some clocks stopped." Oakland Tribune, 2 July 1911, p. 17	I = 5 Felt by and frightened many; small objects moved but did not overturn; hanging pictures swung out of place. USGS.
Livermore		I = 5 A few small objects fell, a few items were thrown from store shelves. USGS.
Newark		I = 5-6 A few dishes fell and broke, a few items were thrown from store shelves, pictures swung out of place, hairline cracks in walls. USGS.
Oakland	I = 5-6 "Many persons ran from their homes Oakland Tribune, 1 July 1911, p. 1. "...(some)plaster fell from ceilings." Stockton Daily Evening Record I July 1911, p. 1.	I = 5-6 ..."Window(s) cracked; a few dishes fell and broke; light furniture overturned; a few items thrown from store shelves. Hairline cracks in walls. USGS.
San Leandro	I = F Felt. The San Francisco Examiner, 2 July 1911	I = 5 A few dishes fell and broke, windows cracked. USGS
CONTRA COSTA COUNTY		
Antioch	I = 5 "Quite a heavy earthquake was felt here.. causing people to rush out of their homes....so gradual did it begin that many people were not aware anything unusual had taken place until it was all over." Antioch Ledger, 8 July 1911, p. 1.	I = 4 Felt by several, frightened few. Hanging objects swung slightly. USGS.
Danville		I = 5 Window(s) cracked, a few di fell and broke. USGS.
Martinez	I = 5-6 "The only damage done was to plastering in several stores and buildings and at the county jail where a bath tub was turned around and a water pipe broken. There was great excitement and people rushed into the strets(sic)." Martinez Daily Standard, 1 July 1911, p. 1.	I = 4-5 Felt by all (at work). USGS
MARIN COUNTY		
San Rafael	I = 5 "...two light shocks of earthquake were felt in this section which caused the people to rush from their buildings. The Journal editor was on the street at the time and did not feel the shocks..." The Marin Journal (San Rafael), 6 July 1911, p. 1.	I = 5 "everybody ran outside (the courthouse)." The Sacramen Bee, 25 April 1984, p. A3. A few items thrown from stor shelves. USGS.
MONTEREY COUNTY		
Castroville	I = F Felt. Oakland Tribune, 2 July 1911, p. 17.	I = 5 Pictures swung out of place small objects fell. USGS.
Marina		I = 6 Hanging pictures fell, many items were thrown from store shelves, hairline cracks in walls. USGS.
Pacific Grove	I = L Slight. Sunday Morning Mercury and Herald (San Jose), 2 July, 1911, p. 2.	I = 5 Window(s) cracked, a few dishes fell and broke. USGS
Salinas	I = 5 No damage. San Francisco Chronicle, 2 July 1911, p. 34. "People in stores and public buildings ran out into...the streets..." Salinas Daily Index, I July 1911, p. 1.	I = 6 Hanging pictures fell, windo cracked, light and heavy fur iture overturned. USGS.

(Table 2 contd)

1911	1984
NAPA COUNTY	
Napa	
I = 5	I = 4-5
"Chandeliers were set swinging, but no damage was done. People by the score rushed from the stores and into the streets for safety." Oakland Tribune, 2 July 1911, p. 1B.	A few small objects overturned but did not fall. USGS
SACRAMENTO COUNTY	
Sacramento	
I = 5-6	I = 3
"...a bookcase was thrown to the floor ... At Fred Rashen's saloon on J Street bottles and glasses were toppled from the shelves and scattered about the floor. Reports from the residence sections are that dishes were tossed about the pantries and quite a number of people became alarmed and fled from their houses ...The ancient and dilapidated brick walls of the City Jail creaked and swayed, pouring down showers of plaster through the crevices and sending the officers on duty running into the open air..." The Sacramento Bee, 1 July 1911, p. 1. "...in many of the reinforced concrete structures it (the earthquake) was not noticed. But in the old frame buildings and tall brick structures it was noted with considerable alarm."; People in the police station fled into the street; "A number of law books were thrown from the shelves in the upper stories of the Bryte building, but other than that no damage was noted." The Sacramento Union, 2 July 1911, p. 13.	"...on the 16th floor of the downtown Resources Building ...curtains swayed away from windows and clipboards hanging from a carousel bobbed as if caught in a strong wind. But among those who didn't even feel the 1:15 p.m. temblor were about a dozen members of the State Seismic Safety Commission who were meeting on the ground floor of the same building..." The Sacramento Bee, 25 April 1984, p. A3.
SAN BENITO COUNTY	
Hollister	
I = F	I = 6
No damage. Santa Cruz Evening News, 1 July 1911, p. 1.	"...a plate glass window in a building across the street jumped from its frame and shattered on the sidewalk below." San Jose Mercury News, 25 April 1984, p. 19A. Several windows broken out; many dishes broke; light furniture overturned; few items thrown from store shelves, hairline cracks in walls. USGS.
San Juan Bautista	
	I = 6
	Hanging pictures fell, window(s) cracked, a few dishes broke, a few items thrown from store shelves, hairline cracks in walls. USGS.
SAN FRANCISCO COUNTY	
San Francisco	
I = 6	I = 6
"In some houses bric-a-brac and glassware were thrown down, but this was not common." San Francisco Chronicle, 2 July 1911, p. 34. "Heavy stones in cornice of the Mechanics Bank building were moved slightly out of alignment; superficial cracks were made in several large office buildings; cornices of the new post office building was disarranged, and minor damage was done to the interior walls of a number of other buildings." The Sacramento Union, 2 July 1911, p. 13.	"Shattered glass fell from windows in the Western Merchandise Mart (an 11-story building on Ninth and Market Streets). San Jose Mercury News, 25 April 1984, p. 20A. "...knocked cornice off a building in the 1600 block of Pacific." San Francisco Chronicle, 25 April 1984, p. 1. At a Pier 39 restaurant "...a few dishes fell from shelves in the kitchen." The Sacramento Bee, 25 April 1984, p. A3. A few dishes fell and broke; some items thrown from store
SAN FRANCISCO COUNTY, San Francisco (contd)	
"...considerable mortar and bricks shook from some of the high buildings." The Evening Pajaronian (Watsonville), 3 July 1911, p. 1. "...on lower Market St., the sidewalk between third and fourth is covered with fragments of cement from rocking buildings." Stockton Daily Evening Record, 1 July 1911, p. 1.	shelves. USGS. (suggests Intensity 5 to the west of Market). Window(s) broken out; many small objects fell. USGS. (1111 Market St., suggests Intensity 6)
SAN JOAQUIN COUNTY	
Lodi	
I = 5	
"The quake either toppled over a gasoline stove, or slopped gasoline from the tank... and the resulting fire destroyed the building..." Stockton Daily Evening Record, 3 July 1911, p. 5.	
Stockton	
I = 6	I = 5
Cracked plaster in the courthouse and other buildings; "...chimney was cracked and one or two of the bricks fell out...Another house...was damaged by the falling chimney." Stockton Daily Evening Record, 1 July 1911, p. 1. "A number of clocks were stopped, people were alarmed and ran into the streets. No damage to buildings of any kind, and but little notice was taken of the shock by the people generally." Anon (1911), p. 110.	Window(s) cracked, a few dishes fell and broke, light furniture overturned, a few items fell from store shelves. USGS.
Tracy	
I = 5-6	I = 5
People ran out, dishes broke, plaster fell from a ceiling. The Evening Mail, (Stockton) 3 July, p. 10.	Felt by and frightened many, window(s) cracked. USGS.

(Table 2 contd)

1911	1984

SAN JOAQUIN COUNTY (contd)

Redwood City

1911	1984
I = 5	I = 5
Short and sharp; "Some people were alarmed..." Times-Gazette (Redwood City), 8 July 1911, p. 1.	A few dishes fell and broke, a few items were thrown from store shelves. USGS.

SAN MATEO COUNTY

Millbrae

1911	1984
	I = 5
	A few small objects overturned, a few items were thrown from store shelves. USGS.

SANTA CLARA COUNTY

Coyote

1911	1984
I = 7-8	I = 7
"...a small frame house was shaken down from a foundation about four feet high, plastering was shaken down from all the plastered houses, a concrete retaining wall at the bridge west of town was cracked off, many windows were broken, clocks were stopped, and dishes, books, and other articles were shaken from their shelves. Near Coyote three county water-tanks about twenty-five feet high and strongly supported were shaken down. Three men are reported to have been shaken from their feet while at work in the fields." Anon (1911), p. 118-119.	Some windows were broken out. Light and heavy furniture was overturned. Many items were thrown from store shelves, Chimney(s) fell. USGS.

NOTE: If the foundation was similar to those at Morgan Hill 1984, described below, then I = VII. This would be consistent with no reports of downed chimneys.

Gilroy

1911	1984
I = 5-6	I = 6-7
"...people as a rule rushed from their homes to the street."; no damage. San Jose Daily Mercury, 3 July 1911, p. 4.	Many items thrown from store shelves, hairline cracks in walls, a single chimney fell a mile west of city limit. (Gilroy building inspector).

ick Observatory	Mount Hamilton
I = 6-7	I = 6-7
Telescope moved 3/4 inch to the south. "The chimneys of a number of the dwelling houses will have to be rebuilt. A large brick building...is also seriously damaged." Oakland Tribune, 4 July 1911, p. 5. "...the walls (of the large brick building) had been weakened by the shocks of 1903 and 1906. The walls of the other brick residences on the mountain were uninjured." Anon(1911), p. 115.	Hanging pictures fell, many items were thrown from store shelves, large cracks in walls. USGS.

Los Gatos

1911	1984
I = 7	I = 6
"Crockery and bric-a-brac was broken in many houses, and plaster fell in some instances. About twenty chimneys were badly cracked and a few overthrown. A portion of a fire-wall was also thrown down." Anon (1911), p. 118.	Hanging pictures fell, many small objects fell, a few items were thrown from store shelves, hairline cracks in walls. USGS.

1911	1984

Madrone

1911	1984
I = 6	
"...a large number of dishes were jarred from their shelves, and clocks were stopped, but no serious damage was done." Anon (1911), p. 119.	

Mayfield

1911	1984
I = 6-7	
Felt. Oakland Tribune, 2 July 1911, p. 17. "...a two story brick building was badly cracked." Sacramento Union, 2 July 1911, p. 20.	

Milipitas

1911	1984
	I = 6
	"...the Elmwood Minimum Securi Barracks suffered major damage, but all inmates were evacuated without injury." San Jose Mercury News, 25 April 1984, p. 20A. Light furniture was overturned, a few items were thrown from store shelves, cracks in chimne and foundation, open cracks in brick wall. USGS.

Morgan Hill

1911	1984
I = 7	I = 7
"...a few windows were broken, clocks stopped, and dishes were shaken from their shelves. A tank and windmill about forty feet high were tilted several degrees out of plumb toward the west. A few chimneys were also reported as having been shaken down. ...two telegraph poles are said to have been broken off at the ground..." Anon (1911), p. 120.	"At least four houses were knocked off their foundations on Oakridye Court and Oakridge Lane in the Jackson Oaks area.." Morgan Hill Times, 25 April 1984, p. 1. "A chimney made of stone a number of years ago... tumbled down." "...pictures fell off walls, the refrigerat toppled and furniture broke. T brick chimney on the 40-year- house fell on the roof." Morgan Hill Times, 25 April 1984, p. Many items thrown from store shelves; chimney(s) fell; larg cracks in walls, many windows broken out USGS. NOTE: Morgan Hill downtown appears to be I=VII (a couple o chimneys fell and furniture broke). The eastern suburb of Jackson Oaks suggests I=VIII because houses fell off cripple walls. But the cripple walls were unbraced and the intensit was probably only VII (see photos in Strykowski and Lichterman (this volume).

Mountain View

1911	1984
	I = 5
	A few small objects overturned and fell. USGS.

Palo Alto

1911	1984
I = F	I = 4-5
Felt. Oakland Tribune, 2 July 1911, p. 17.	Felt by and frightened many. USGS.

(Table 2 contd)

SANTA CLARA COUNTY, Morgan Hill (contd)

San Jose

1911	1984
I = 6-7	I = 6
"...the only damage reported was several cracked windows and fallen plaster." San Francisco Chronicle, 2 July 1911, p. 34. "No serious damage to any buildings here (San Jose) or vicinity so far as learned: some fallen plaster and one or two chimneys twisted or fallen, some large glass windows broken and druggists stock and crockery thrown from shelves." The Sacramento Union, 2 July 1911, p. 20. "Here and there bricks were dislodged from the crests of old buildings, plaster was cracked and many plate glass windows were demolished. Glassware and crockery in stores were dislodged from shelves and a considerable loss was suffered by various merchants in this manner." Sunday Mercury and Herald (San Jose), 2 July 1911, p. 1.	"Both the Santa Clara County Building and the San Jose City Hall were temporarily evacuated after cracks were found in some walls (no gass was broken, but plaster fell). San Jose Mercury News, 25 April 1984, p. 20A. Many dishes fell and broke; many items thrown from store shelves; pictures fell; chimney(s) cracked. USGS. "A dresser drawer fell...as the quake shook glass nicknacks off the walls and dumped dishes from cabinets onto the floor." San Jose Mercury News, 25 April 1984, p. 19A.

San Martin

1911	1984
I = 5	I = 6-7
The earthquake "...broke a few dishes by jarring them from their shelves." Anon (1911), p. 120.	"...had hundreds of cans of paint topple off shelves and splatter on the floor, making a huge gooey mess. San Francisco Chronicle, 25 April 1984, p. 2. Many dishes broken; heavy furniture overturned; many items thrown from store shelves; chimney(s) fell; large cracks in dry wall. USGS.

Santa Clara

1911	1984
I = 7	I = 6
"Several chimneys about town fell down and a number of windows were demolished." Sunday Mercury and Herald (San Jose) 2 July 1911, p. 2.	Many small objects fell, a few dishes fell and broke, a few items were thrown from store shelves, hairline cracks in walls, chimney(s) cracked. USGS.

Stanford University

1911	1984
I = 5-6	
Plaster cracked. San Francisco Chronicle, 2 July 1911, p. 34. "...Dislodging of plaster ceilings..." Sacramento Union, 2 July 1911, p. 20. "In the chemical lab. some plaster that was already loose was thrown to the floor." Anon(1911), p. 120.	

SANTA CRUZ COUNTY

Boulder Creek

1911	1984
I = 5	I = 5
"...in some of the grocery stores about town a few canned and bottled goods were thrown from the shelves.; ...startled people rushed from the business places to the street..." Anon (1911), p. 119-120.	Person frightened and had difficulty standing. Building shook strongly and pictures swung. USGS.

Corralitos

1911	1984
	I = 6
	Window(s) cracked, many small objects fell, a few dishes broke, hairline cracks in walls, chimney cracked. USGS.

Santa Cruz

1911	1984
I = 6	I = 6
"Many of the people were alarmed and ran out of the stores and houses, and some clocks were stopped." Anon(1911), p. 120. "A keystone fell from one of the windows in the second floor of the Staffler building,...." In the same building the wall was set in slightly near the north wall."; two plate glass windows cracked. Santa Cruz Evening News, 1 July 1911, p. 1.	Window(s) broken out, a few items thrown from store shelves, chimney cracked, large cracks in brick veneer. USGS. Felt indoors but not outdoors. The Sacramento Bee, 24 August 1984, p. A3.

Watsonville

1911	1984
I = 5-6	I = 6
"...caused a number of clocks to stop and many main street buildings to crack and sway." Anon(1911),p. 120. The Evening Pajaronian (Watsonville), 1 July 1911, p. 8. "...the telephone girls ran into the street, as did, in fact, everybody inside a house, and there was a general panic..." Santa Cruz News, 1 July 1911, p. 1.	Many items were thrown from store shelves, large cracks in interior walls. USGS.

SOLANO COUNTY

Dixon

1911	1984
	I = 5
	Window(s) cracked, few items thrown from store shelves. USGS.

Mare Island

1911	1984
I = 4-5	
Stopped a clock. Anon (1911), p. 110.	

Rio Vista

1911	1984
I = 6 (RF) (Rossi Forel)	
6 RF (no description) Anon (1911), p. 110.	

Glen Ellen

1911	1984
	I = 5
	Window(s) cracked, few dishes broke, few items thrown from store shelves. USGS.

(Table 2 contd)

1911	1984
STANISLAUS COUNTY	
Modesto	
I = 5-6	I = 5
"Employees of the stores on the business streets and the officials and their deputies at work in the court house rushed to the streets..." The Modesto News, 1 July 1911, p. 1. "...the populace generally lost no time in getting to the middle of the street, much to the surprise of those who happened to be on the street at the time, as those who were out of doors or moving about did not feel the shock."; "No damage was reported locally with the exception of some fallen plaster in the old Wood building, over the Wood hardware store." Modesto Morning Herald, 2 July 1911, p. 1.	Felt by and frightened many (at work); window(s) cracked; a few small objects fell. USGS
Patterson	
	I = 5
	A few dishes fell and broke, a few items were thrown from store shelves. USGS.
YOLO COUNTY	
Winters	
I = 5	
Stopped several clocks. The Sacramento Union, 2 July 1911, p. 20.	

PRINCIPAL FEATURES OF THE STRONG-MOTION DATA FROM THE 1984 MORGAN HILL EARTHQUAKE

by

A.F.Shakal, R.W. Sherburne and D.L. Parke[1]

ABSTRACT

A strong directional dependence that can be correlated with the geometry of the earthquake fault rupture is exhibited by the strong motion data from the Morgan Hill earthquake. Higher accelerations were recorded at stations to the southeast of the earthquake than to the northwest. One of the southeast stations, Coyote Lake Dam, recorded a peak horizontal acceleration of 1.3 g. This acceleration exceeds that of the Pacoima Dam record from the 1971 San Fernando earthquake, the previous largest horizontal acceleration recorded. However, the peak velocity and displacement, as well as the duration, of the Coyote Dam record are less than those of the Pacoima Dam record. The records from the Gilroy strong motion array, also to the southeast of the earthquake, exhibit unusual high vertical accelerations. They also show alluvial amplification effects similar to those observed in corresponding records from the 1979 Coyote Lake earthquake. In addition to the ground motion data, many recordings of structural response to the ground shaking were obtained during this earthquake. These records provide unprecedented data for analysis of the rocking and torsional motion of structures as well as structural amplification.

INTRODUCTION

The Morgan Hill earthquake was a moderate (6.2 M_L BRK) strike-slip earthquake which occurred on the Calaveras fault southeast of San Jose on April 24, 1984. It triggered the largest number of strong motion instruments since the San Fernando earthquake of 1971. Accelerograms were recovered from a total of nearly 70 stations, including 48 of the California Strong Motion Instrumentation Program (CSMIP) of the Division of Mines and Geology and 19 of the Seismic Engineering Branch of the U.S. Gelogical Survey (USGS). The CSMIP stations which recorded the Morgan Hill earthquake are indicated in Figure 1 (from Shakal et al., 1984). These stations are complemented by those maintained by the USGS and discussed by Brady et al. (1984), the closest of which is the station at Anderson Lake Dam. The greatest damage, and possibly the highest acceleration, occurred in an area near the southern end of Anderson Lake, where no accelerograph stations were located. Temporary accelerographs were installed in that area by both the CSMIP and USGS following the mainshock. Unlike the Coalinga earthquake of May 1983, the Morgan Hill event was followed by

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very few aftershocks over magnitude 4.0, and as a result few accelerograms were obtained from aftershocks.

DIRECTIONAL DEPENDENCE

The Morgan Hill earthquake was recorded by a relatively complete azimuthal distribution of accelerograph stations, as indicated in Figure 1. When the peak acceleration data are considered as a function of distance, a significant difference becomes apparent between the acceleration data from stations to the southeast of the earthquake as compared with data from stations to the northwest. Figure 2 shows the peak acceleration data plotted against the distance of the stations from a point on the fault at the approximate center of the aftershock zone. The data plotted in Figure 2 include the peak acceleration data listed in Table 3 of Shakal et al. (1984) and in Table 1 of Brady et al. (1984). Figure 2 shows that for stations at the same distance, peak accelerations from the southeastern stations are higher than for the northwestern stations.

The earthquake origin has been estimated (Cockerham et al., this volume) to be located at 37.31N, 121.68W, about 4 km southeast of the Halls Valley accelerograph station. The timing on the records from the near-in accelerographs indicates that the rupture propagated from the origin toward the southeast, toward Morgan Hill and Coyote Lake (Bakun et al., 1984). The southern stations in Figure 2 are thus in the direction of rupture propagation, and the northern stations are opposite the direction of rupture propagation. Earthquake source theory indicates that a propagating rupture would cause a directivity in the close-in radiated energy, with increased amplitudes occurring at points ahead of the rupture. Studies of this effect, called directivity focusing, have been mostly limited to analytical modelling (e.g., Boore and Joyner, 1978) because of the paucity of empirical observations. The Morgan Hill data represent the first strong-motion data set in which this effect may be clearly observed, possibly because of the relatively complete azimuthal distribution of accelerograph stations. If directivity did in fact contribute to high accelerations which occurred in this event, then the question of whether similar high accelerations may be expectable from future strike-slip earthquakes is pertinent The high acceleration record from the Coyote Lake Dam station, in particular, warrants careful analysis.

COYOTE LAKE DAM ACCELEROGRAM

The accelerogram recorded at the Coyote Lake Dam accelerograph station, shown in Figure 3, had a horizontal peak acceleration value of 1.3 g; the previous highest horizontal acceleration was recorded during the 1971 San Fernando earthquake at the Pacoima Dam accelerograph station (1.25 g). It is important to place the Coyote Lake Dam record in perspective relative to that record as well as consider the possibility of any anomalous aspects of the instrument or the site conditions.

Verification Investigations

The Coyote Lake Dam accelerograph station is located near the left (northwest) abutment of the Coyote Lake Dam, an earthen dam at the northern end of the lake. The station itself is sited near a rock promontory against which the dam embankment is located. The accelerograph site and a topographic map of the surrounding area are shown in Fig. 4. Photographs taken during construction of the dam in 1935 (R. Tepel, personal communication, 1984) indicate that the promontory is the exposed top of a rock mass that extends downward to at least the bottom of the excavation for the dam (approximately 40 m, or 120 ft). The accelerograph station was installed at its present location in 1975.

As the initial step in an investigation of the recording conditions, the recording accelerograph was removed from the station for laboratory testing shortly after the earthquake. The instrument is an SMA-1 (Kinemetrics) strong-motion accelerograph, manufactured in 1976 and installed at the site the same year. Static (tilt) tests of the instrument sensitivity and standard calibrations of natural frequency and damping indicated normal instrument behavior. Comparison tests of the dynamic response were performed by attaching the Coyote instrument and others to a common platform and comparing the records obtained when the platform was (manually) shaken; no significant differences were observed.

The most definitive way to determine whether anomalous accelerograms are caused by local site effects is to obtain comparison records from a nearby site. Toward this end, a temporary station was installed approximately 300 m from the existing station shortly after the earthquake; unfortunately there have been no aftershocks of sufficient size to trigger either instrument. It is worth noting, however, that an accelerogram was recorded at the Coyote Dam permanent station during the 1979 Coyote Lake earthquake by the same instrument, at the same orientation, as the 1984 record. That record (shown in Fig. 5) has a peak acceleration of 0.25 g and no anomalous characteristics of the record have been proposed.

Field investigations at the site revealed some surficial cracking in the vicinity of the recording station, as illustrated in Fig. 6. The tensional nature of these cracks and their orientation (approximately sub-parallel to the promontory-fill boundary) suggest that they resulted from settling of the dam infill during the earthquake shaking. A vertical survey along the crest of the dam performed after the earthquake (Tepel et al., this volume) indicates settlement reached a maximum of approximately 6 cm near the crest center.

To summarize the results of investigations of recording conditions made to date, no obvious cause has been found to explain anomalous high accelerations at the site. It should be noted however, that the rock promontory near the station is a large, weathered unit, with several old faults and joints. It is possible that these could become surfaces of motion during strong shaking; motion on these surfaces could conceivably lead to short-duration,

high acceleration pulses.

Comparison with 1971 Pacoima Dam Accelerogram

Peak acceleration is only one parameter characterizing a strong motion record. The velocity and displacement records computed from the 1984 Coyote Lake Dam record and the 1971 Pacoima Dam record are compared in Figure 7. The comparison is between the components with the highest acceleration and velocity for each accelerogram. Peak-value comparisons (acceleration, velocity and displacement) for all three components are given in Table 1. These time-history comparisons indicate that although the 1984 record has a higher peak acceleration, the 1971 Pacoima Dam record has a greater peak velocity and significantly greater displacement. In addition, the duration of shaking in the 1984 record is significantly shorter than that of the 1971 record (approximately half that of the 1971 record, if a 0.10 g threshold is used, as indicated in Table 1).

TABLE 1

COMPARISON OF THE 1984 COYOTE DAM ACCELEROGRAM AND THE 1971 PACOIMA DAM ACCELEROGRAM

	Maximum Acceleration (g)	Maximum Velocity (cm/sec)	Maximum Displacement (cm)	Duration (secs > 0.10g)
<u>1984 Coyote Dam Accelerogram</u>				
Horizontal #1 (285 deg.)	1.30	80.	10.	6.4
Horizontal #2 (195 deg.)	0.71	52.	10.	4.6
Vertical	0.40	15.	3.	5.0
<u>1971 Pacoima Dam Accelerogram</u>				
Horizontal #1 (S16E)	1.24	113.	38.	11.0
Horizontal #2 (S74W)	1.25	58.	11.	11.1
Vertical	0.72	58.	19.	9.6

* Note: Peak accelerations are the Volume 1 values (e.g., Hudson, 1976) Component orientations given by azimuth (clockwise from North) for the Coyote record, and bearing (from Hudson, 1976) for the Pacoima record

The response spectra for the two records are compared in Fig. 8 for all three components. It is particularly interesting to compare the response spectra for the first horizontal component, corresponding to the records shown in Fig. 7. The response spectra

for these two components are quite similar for frequencies above about 1.0 hz (i.e., for short periods, 1.0 second and less). However, at longer periods, over 1.0 second, the 1984 Coyote Lake Dam spectrum is significantly lower than the Pacoima spectrum (approximately a factor of three difference at 4.0 second period). The smaller spectrum at long periods is reflected in the smaller displacements in the Coyote Dam time history (Fig. 7).

The response spectra for the second horizontal components are more similar at the longer periods, and this is reflected in the more similar values of peak velocity and peak displacement (Table 1). The vertical component spectra, as well as the time-history values in Table 1 indicate that the vertical motion was significantly stronger in the 1971 Pacoima record, regardless of how the motion is parameterized.

STRONG MOTION DATA FROM THE GILROY ARRAY

An alignment of strong-motion accelerographs was installed across the Santa Clara Valley near Gilroy in the mid 1970s. The array extends from high-velocity Franciscan materials at the western edge of the valley, across the alluvial valley floor, and onto high velocity materials on the eastern edge of the valley. This array is a cooperative effort of the California Strong Motion Instrumentation Program (CSMIP) and the USGS Seismic Engineering Branch, and is currently instrumented and maintained by CSMIP. Prior to the Morgan Hill event, the array recorded the 5.9 ML Coyote Lake earthquake of August 6, 1979 (Porcella et al., 1979) so the array has provided two suites of records in only the ten years since it was installed.

The Gilroy array records from the Morgan Hill earthquake show horizontal accelerations of 0.20 - 0.40 g in the central part of the alluvial valley, with reduced amplitudes at the margins of the valley. Peak accelerations, horizontal and vertical, are listed in Table 2 for the Gilroy array stations for both the 1984 and 1979 earthquakes. It is particularly interesting to compare the records from the two stations on the west edge of the valley which were considered by Joyner et al. (1981) in an analysis of data from the 1979 earthquake. In that event, the horizontal amplitudes at Station #2, on the valley floor, were approximately twice those at Station #1, on Franciscan. That ratio is explained by Joyner et al. (1981) as being due to the conservation of energy in the wavefront (dependent on the S-wave impedances of the soil and rock). As indicated in Figure 9, the 1984 records show nearly the same ratio (2.2) of the horizontal amplitudes. (For both earthquakes, the distance between stations (2 km) is small compared to the distance to the source - approximately 20 km in 1984, 10 km in 1979).

The vertical amplitudes are unusually high in the Gilroy array accelerograms from the Morgan Hill earthquake. The peak vertical acceleration is generally observed to be one-third to two-thirds of the peak horizontal in strong motion records (e.g., Housner, 1970). In contrast, in the 1984 Gilroy array records the vertical peak acceleration is as large or larger than the horizontal; in the Station #2 record the vertical peak is nearly three times the

horizontal. The high amplitude vertical phase in the Station #2 record (see Fig. 9) is similar to that on the other Gilroy array records: a high-frequency, high-amplitude phase arriving 1-2 seconds after triggering and several seconds before the high amplitude phase (S?) on the horizontals. In the 1979 records, Station 4 also had high-frequency, high-amplitude vertical motion (0.44 g), with lower amplitudes on the horizontals (0.26 g). The other array stations did not record a similar high amplitude vertical phase, however. Thus, the high-frequency, high-amplitude vertical motion is not as clearly a source-independent characteristic as is the increased horizontal shaking in the alluvial valley.

TABLE 2

GILROY ARRAY PEAK ACCELERATIONS FROM THE 1979 AND 1984 EARTHQUAKES

	Morgan Hill Earthquake of April 24, 1984			Coyote Lake Earthquake of August 6, 1979		
STATION	Horiz.	Vert.	V/H	Horiz.	Vert.	V/H
Gilroy #7 Mantelli Rnch.	0.19	0.46	2.4	--	--	--
Gilroy #6 San Ysidro Micro.	0.34	0.43	1.3	0.42	0.17	0.4
Gilroy #4 San Ysidro Schl.	0.37	0.40	1.1	0.26	0.44	1.7
Gilroy #3 Sewage Plant	0.20	0.40	2.0	0.27	0.15	0.6
Gilroy #2 M.T. Motel	0.22	0.61	2.8	0.26	0.18	0.7
Gilroy #1 Gavilan H2O Tank	0.10	0.10	1.0	0.13	0.08	0.6

STRUCTURAL RESPONSE DATA

In addition to the free-field strong motion data which have been discussed, the data set from the Morgan Hill earthquake is also noteworthy for the large proportion of records obtained from structures. More structural response records were obtained from this event than from any since the 1971 San Fernando earthquake. Also, in contrast with the three independent accelerographs located in buildings at that time, the structural data from this event involve simultaneous recordings of the motion occurring at many points throughout a building. These records will allow the detailed analysis of structural amplification of the motion as well as any rotation or torsional response of the structures. Detailed information describing the instrumentation and the Morgan Hill accelerograms is available in Shakal et al. (1984) and Brady et al. (1984). However, to provide an overview of the structural response data, Table 3 provides a listing of selected structures recorded by common-timed accelerograph systems and the amplitude of the motion

at the base and the roof (or top) of each structure. The number of sensors and the height of each structure are also indicated.

TABLE 3

SELECTED STRUCTURAL RESPONSE RECORDS
FROM MORGAN HILL EARTHQUAKE

Structure	No. Stories	No. Sensors	Peak Acceleration Base	Top	Agency
San Jose - Santa Clara County Office Bldg.	13	22	0.04H, 0.02V	0.18H	1
San Jose - Town Park Towers Apt. Bldg.	10	13	0.06H, 0.05V	0.22H	1
San Jose - Great Western S&L Bldg.	10	13	0.06H, 0.04V	0.22H	1
Saratoga - West Valley College Gymnasium	1	11	0.10H, 0.03V	0.42H	1
Watsonville - Phone Co. Office Bldg.	4	13	0.11H, 0.09V	0.33H	1
Hollister - Glorietta (Tilt-Up) Warehouse	1	13	0.11H, 0.31V	0.25H	1
San Bruno - Postal Services Bldg.	9	16	0.03H, 0.02V	0.11H	1
So. San Francisco - Kaiser Med. Bldg.	4	11	0.03H, 0.02V	0.26H	1
San Francisco - Transamerica Bldg.	58	12	0.02H, 0.01V	0.10H	2
Morgan Hill - Anderson Dam (Earthen)	--	6	0.41H, 0.20V	0.63H	2
San Jose - 101/680/280 Freeway Interchange	--	12	0.12H, 0.08V	---	2
San Justo - Dam Site	--	6	0.07H, 0.03V	0.08H	2
Los Gatos - Lexington Dam (Earthen)	--	9	0.02H, 0.01V	0.04H	1
Oakland - 14th St. Wharf	--	12	0.04H, 0.02V	---	1
Oakland - Caldecott Tunnel	--	19	0.01H, 0.01V	---	1

Agency: 1 - CSMIP, Ca. Div. Mines & Geol. 2 - SEB, U.S. Geol Surv.

ACKNOWLEDGEMENTS

Post-earthquake laboratory tests of the Coyote Lake Dam accelerograph were performed by G. Guyer and W. Williams. G. Guyer helped reconstruct the history of the Coyote accelerograph site to determine the instrument orientation at the time of the 1979 Coyote Lake earthquake.

Mr. Robert Tepel of the Santa Clara Valley Water District provided useful dam construction photographs and early report information. Glenn Borchardt and Richard Boylan assisted in mapping and interpretation of the cracks at the Coyote Dam site.

B. Tucker and J. Bennett reviewed the manuscript and made valuable suggestions which led to improved clarity.

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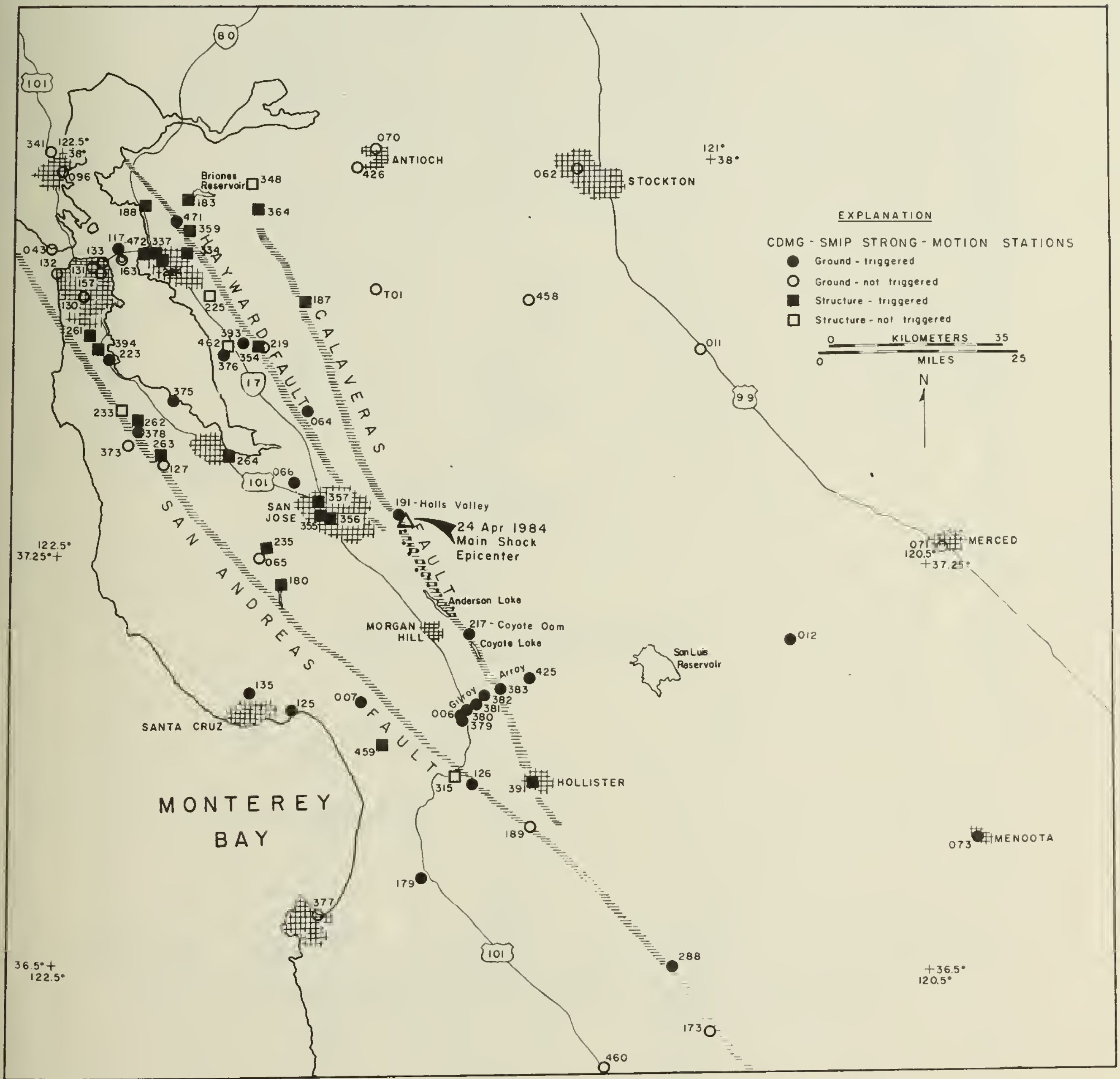

Fig. 1 CDMG strong-motion stations, the Morgan Hill epicenter, and aftershock zone (stipled). Stations are identified by 3-digit code listed in Shakal et al. (1984).

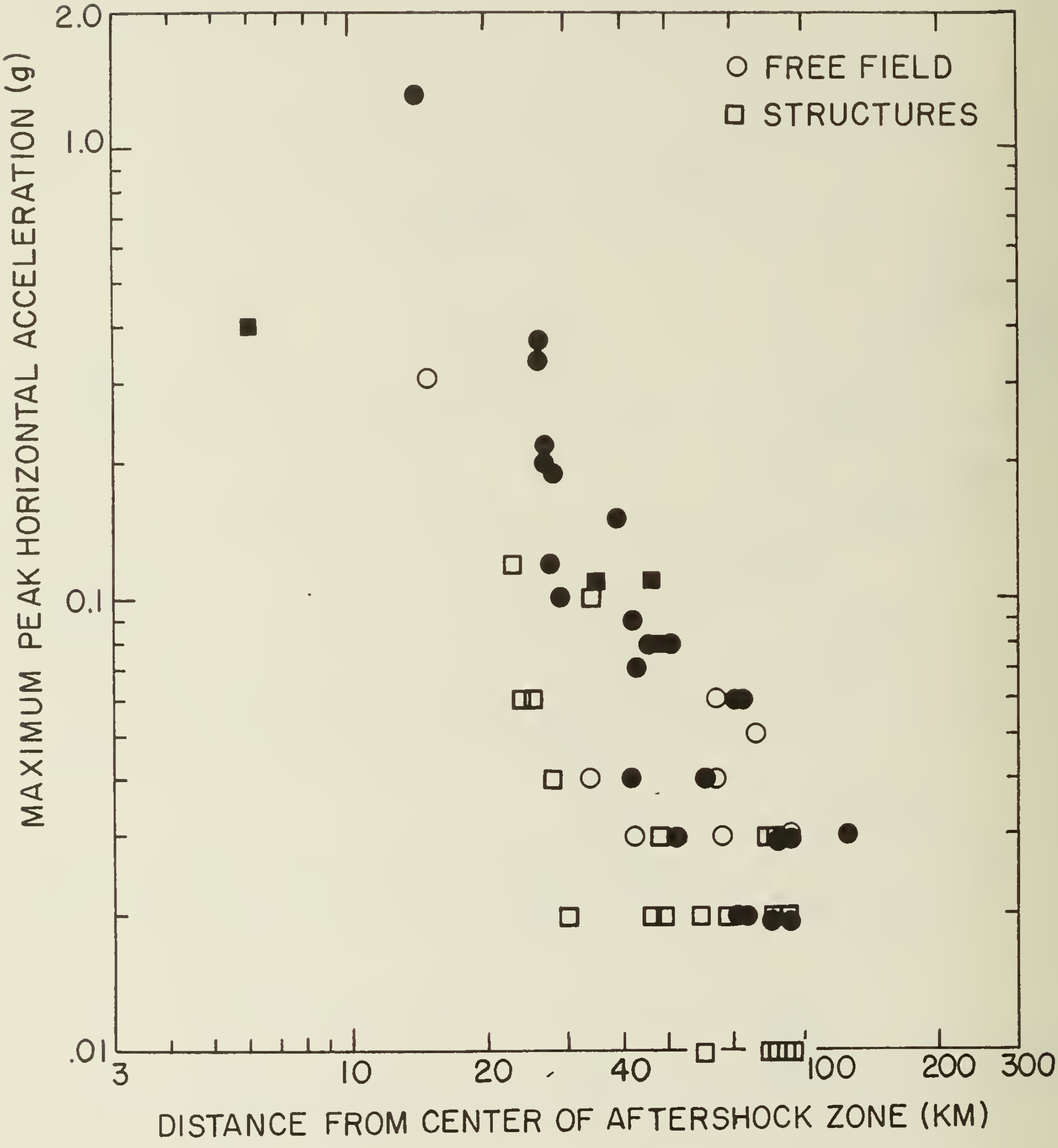

Fig. 2. Peak horizontal acceleration from the Morgan Hill earthquake. Distance is measured from a point (37.217N, 121.640W) on the fault at the approximate center of the aftershock zone. Solid symbols correspond to stations southeast of that point, open symbols to northwest stations.

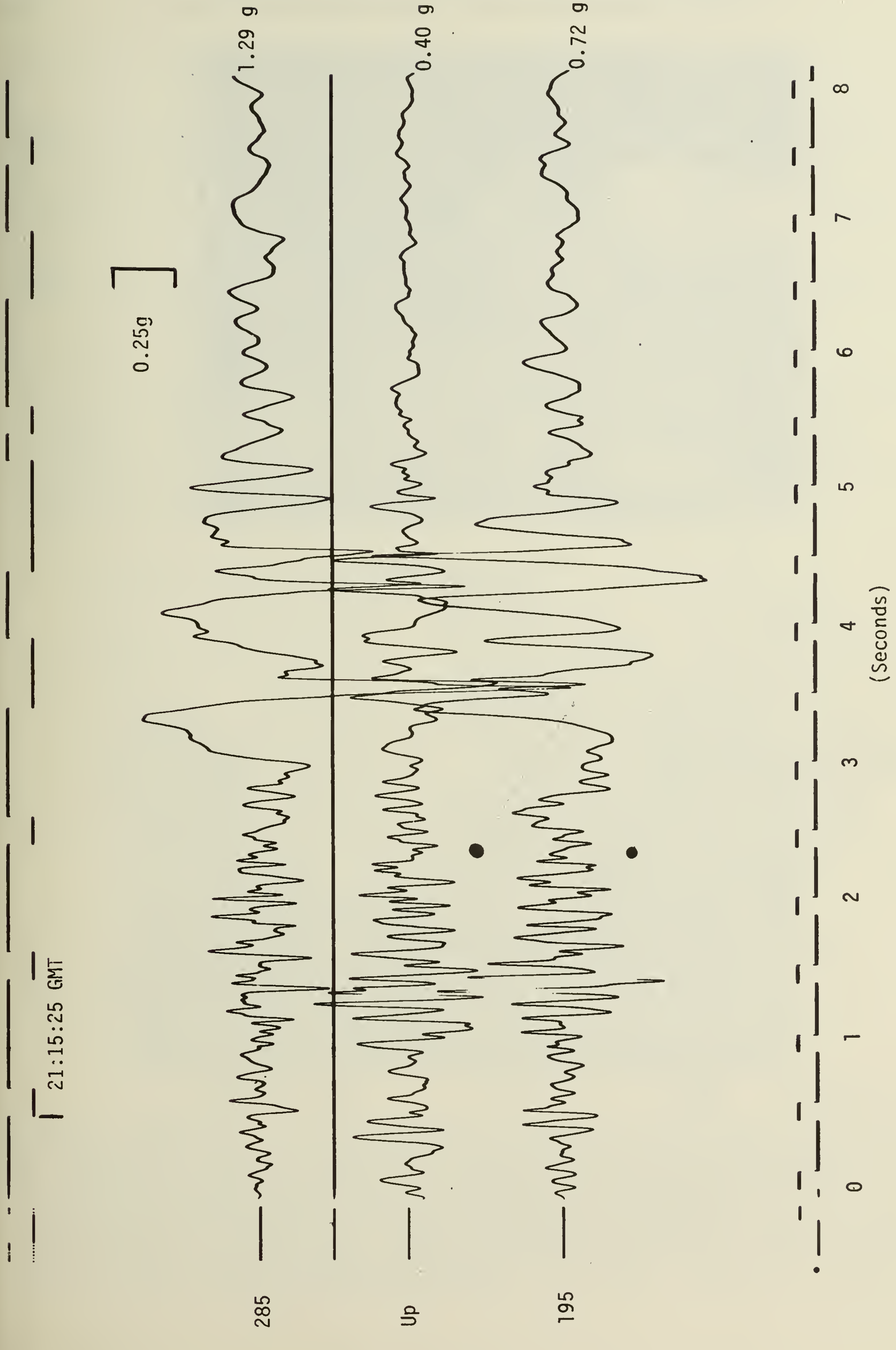

Fig. 3. The accelerogram recorded at the Coyote Lake Dam during the Morgan Hill earthquake of April 24, 1984.

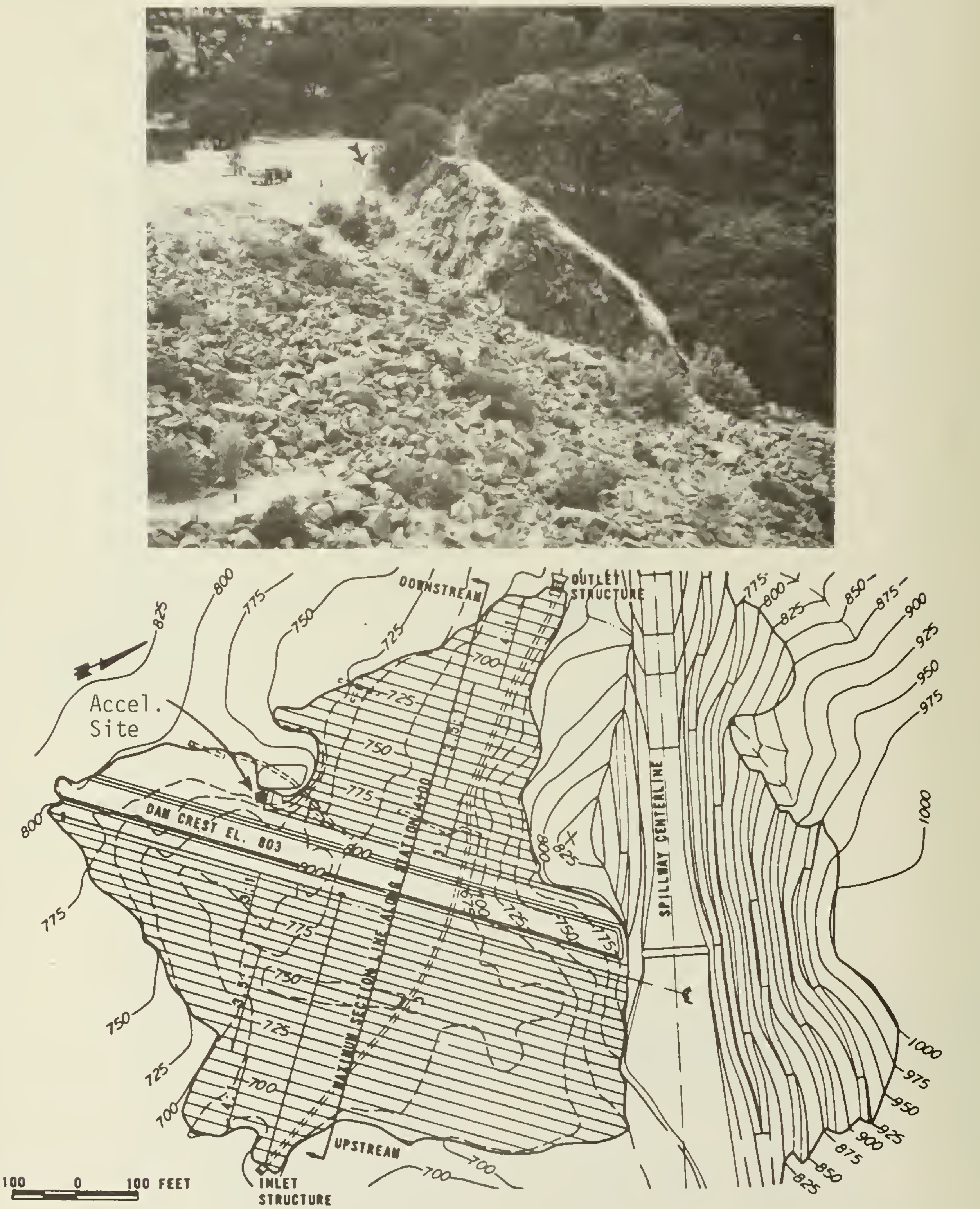

Fig. 4. (Upper) Photograph of accelerograph site at Coyote Lake Dam showing the strong-motion instrument shelter (arrow) near the rock promontory, with the rock riprap on the downstream face in the foreground. (Lower) Topography in the vicinity of Coyote Lake Dam, based on 1937 as-built drawings (from Buangan and Wahler, 1980; 25 foot contour interval). The approximate location of the instrument shelter is indicated. The upper photo was taken from the right abutment (near the 'x'), across the dam toward the rock promontory.

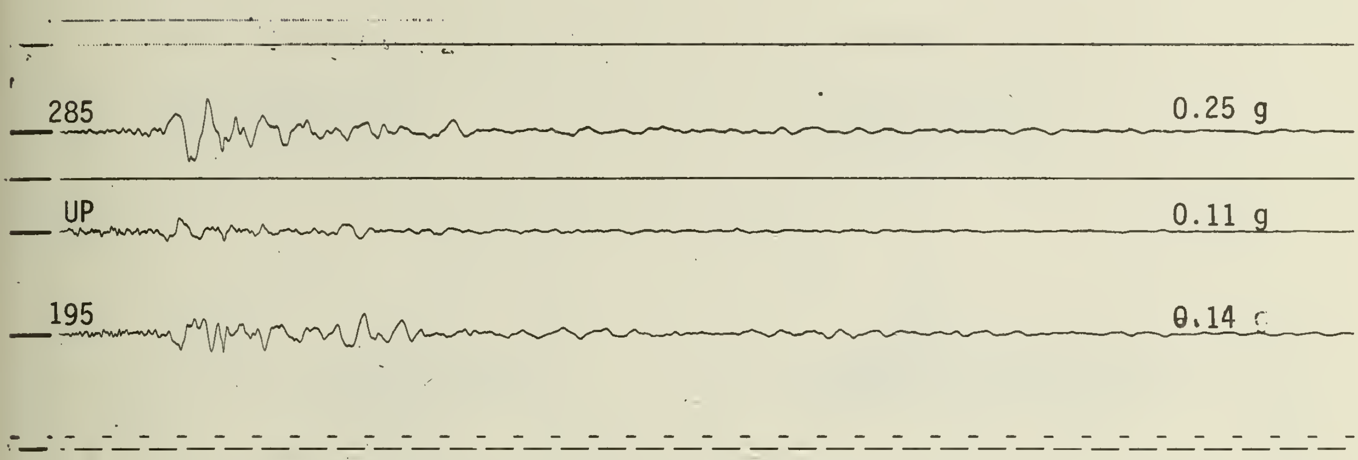

Fig. 5. Accelerogram recorded at the Coyote Lake Dam during the 1979 Coyote Lake earthquake. This accelerogram was recorded at the same site, with the same instrument at the same orientation, as the 1984 accelerogram shown in Fig. 3. The epicenter of the 1979 event (August 6, 5.9 ML) was approximately 2 km distant from this station. (Note that the instrument orientation given here for the 1979 record corrects that listed in Porcella et al. (1979))

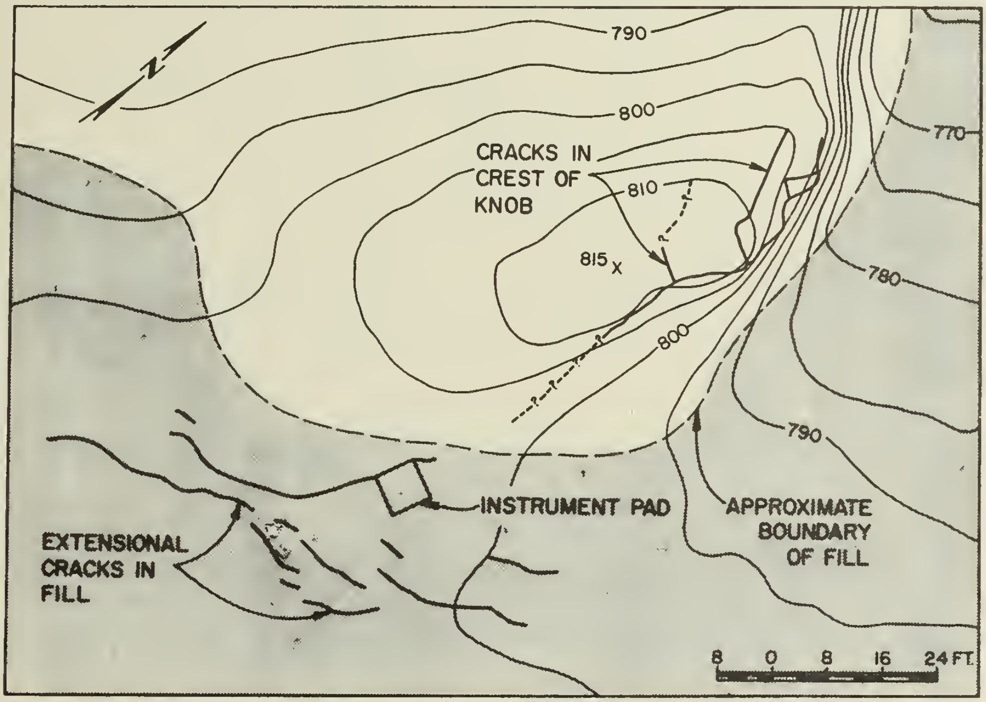

Fig. 6. Topography in the immediate vicinity of the Coyote Lake Dam accelerograph site, from the 1937 as-built drawings (see Fig. 4). The surficial cracks observed in the vicinity of the instrument pad following the earthquake are also shown. They are extensional in nature (typically near 1 cm in width) without observable vertical or translational displacement. Also shown are apparently pre-existing cracks in the rock promontory, or knob, which may have undergone motion during the earthquake shaking.

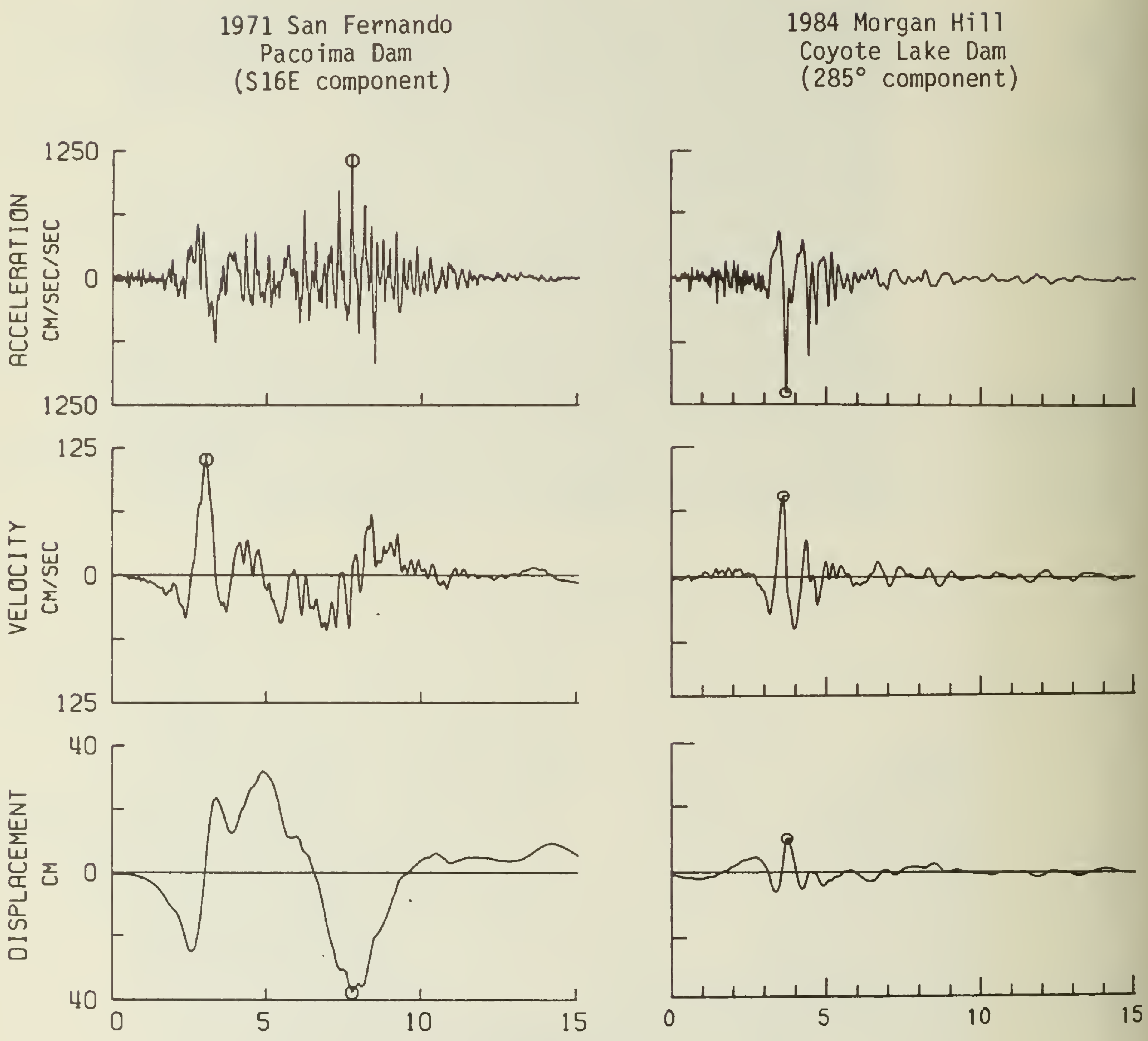

Fig. 7. Acceleration, velocity and displacement time histories computed from the 1971 San Fernando accelerogram from Pacoima Dam (S16E component, left) and the 1984 Morgan Hill accelerogram from Coyote Lake Dam (285 degree component, right).

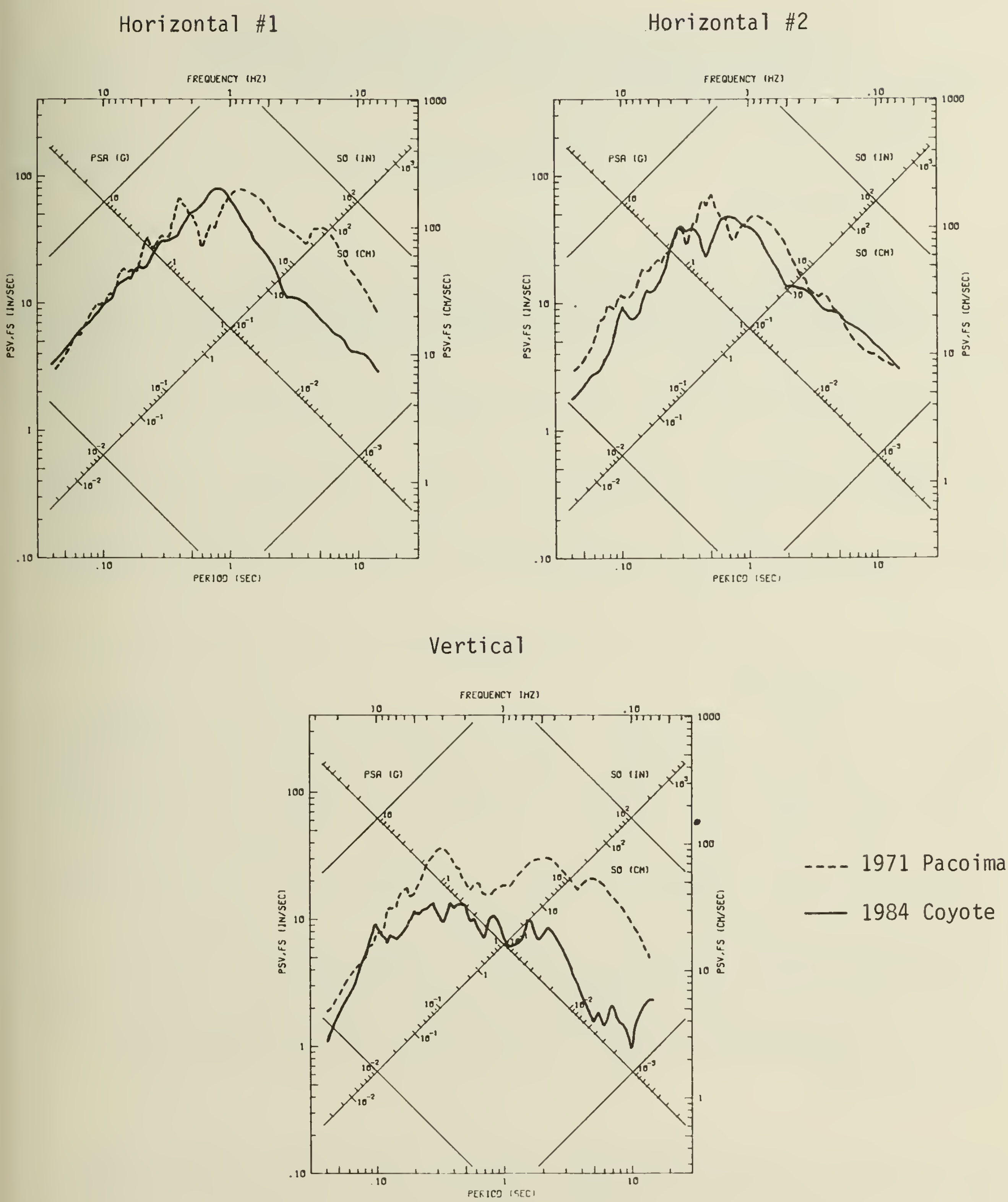

Fig. 8. Response spectra (5% damping, PSRV) for all three components of the 1984 Coyote Lake Dam accelerogram (solid) and the 1971 Pacoima accelerogram (dashed). The upper pair are the horizontal components; the leftmost corresponds to the high amplitude components (1.3g for the Coyote record) shown in Fig. 7.

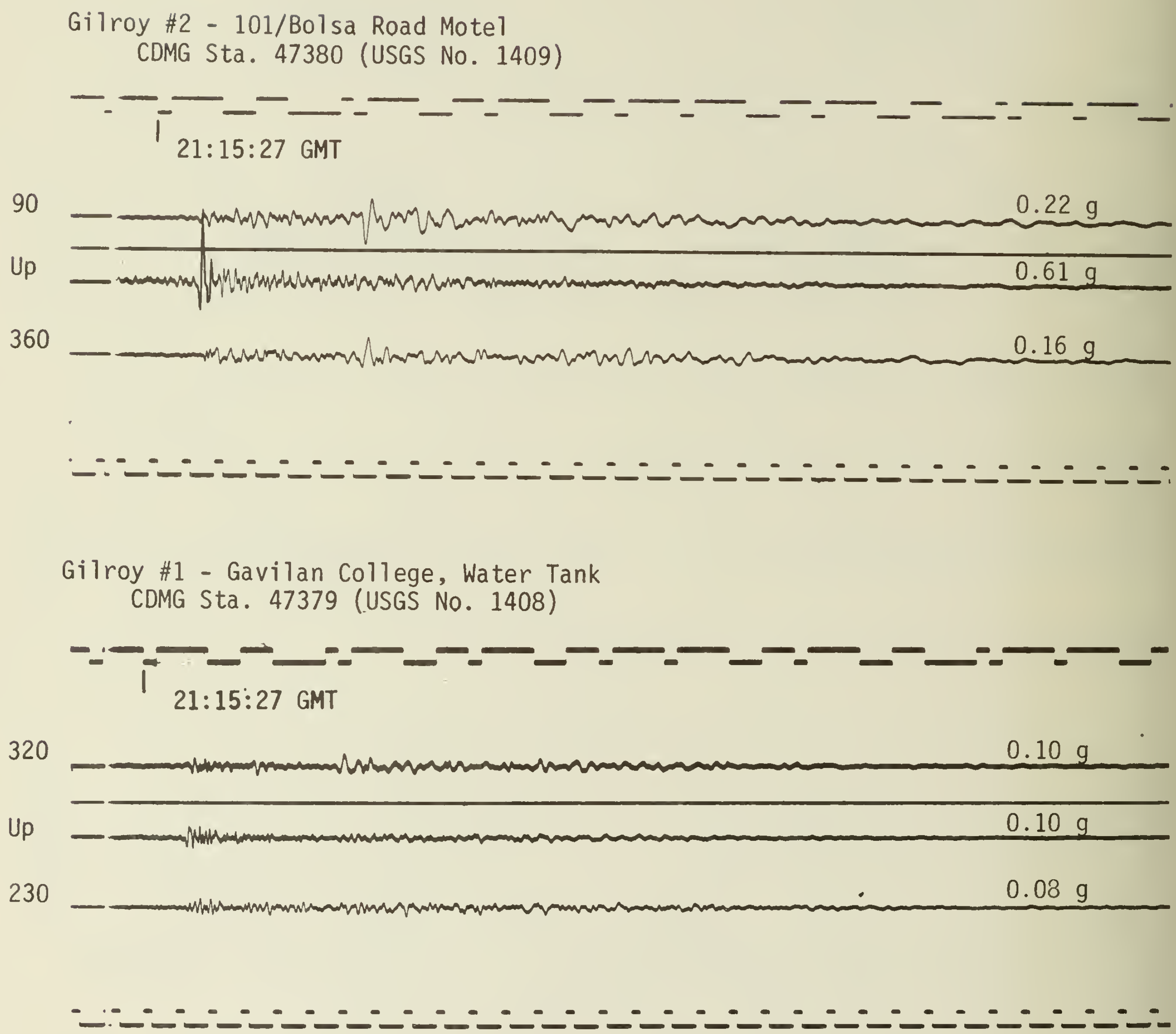

Fig. 9. Accelerograms recorded at Gilroy Array Station #2 (upper), on alluvium, and Station #1 (lower), on Franciscan, during the 1984 Morgan Hill earthquake.

RADIAL ASYMMETRY OF THE OBSERVED PGA AND QUESTION OF FOCUSING IN THE NEAR-SOURCE REGION OF APRIL 24, 1984 MORGAN HILL EARTHQUAKE

by

Mansour Niazi*

ABSTRACT

The observed enhancement in the southeast direction from the source of the general level of recorded PGA provides qualitative indication of focusing of seismic energy in that direction. In order to explore means of examining this suggestion quantitatively, the observed peak horizontal accelerations within 50 km of the rupture plane are expressed in terms of their residuals from the predicted mean relative to the standard deviation of a single observation, using standard empirical ground motion predictions. If focusing were the major contributing factor in producing the observed PGA variation, the residuals would generally be expected to correlate with geometrical configuration of incident ray relative to the rupture surface with dynamics of faulting as a parameter. This concept has been examined for the 1984 Morgan Hill observations. Results are compared with those of a similar test for the 1979 Imperial Valley earthquake for which peak particle velocities rather than peak ground accelerations revealed a tendency for focusing.

INTRODUCTION

The April 24, 1984, Morgan Hill earthquake has been cited to have produced the largest peak recorded horizontal ground-motion (1.3 g) to date. Seismic focusing, local topography, mass and shape of Coyote Dam and ground disturbance at the observation site (Coyote Dam crest) have been cited as possible reasons for such a large acceleration (Shakal et al. 1984a and b). The apparent enhancement in the level of recorded peak accelerations in the southeast direction of the source relative to those observed in the north-northwest azimuths is similar to that expected for focusing of seismic energy produced by a coherent southeast moving rupture. In order to examine the effect of focusing and quantify the contribution of individual observations to the observed pattern, they are initially compared with their respective predicted value determined empirically. The resulting residuals are then examined for the effects of geometrical and dynamic parameters which influence focusing. A previous application of this procedure to the observations of the 1979 Imperial Valley earthquake failed to show a discernible trend for high frequency near-source PGA data, whereas it provided evidence for focusing of lower frequency waves contributing to observations of peak ground velocity (Niazi, 1982).

Estimation of Residuals

Using source parameters and rupture surface configuration defined by the distribution of aftershocks (Bakun et al., 1984), significant distances of observation points from the fault plane, as defined by Campbell (1981) were estimated. The mean observed horizontal

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PGA values of the accelerations were then subjected to non-linear regression against the calculated distances following Campbell's formulation. Only data points recorded at significant distances equal to or less than 50 km were included in the regression analysis. The shallowest approach of rupture in the basement rock is taken at a depth of 3 km. The resulting equation which provides empirically based predictions at individual stations for the M_L 6.2 Morgan Hill earthquake has the following form:

$$\ln PGA = 1.562 - 1.312 \ln (R + 2.53)$$

with $\sigma = 0.62$.

Table I contains a listing of data points, their significant distances, observed PGA and the calculated residuals. The column under focusing potential is defined as $(\beta/V\text{-}\cos\alpha)^{-1}$, where V is rupture velocity, β shear velocity and α the angle between the rupture propagation vector positioned at the hypocenter and the seismic ray arriving at the observation site. A somewhat different approach, based on PGA rms acceleration observed for two nearby sources was used by Boatwright and Boore (1982) for estimation of the focusing effect.

The content of Table I is arranged in order of increasing residuals, and with some exception shows a parallel increase in the estimated focusing potential. Our trial model is unilateral propagating rupture at a speed of 0.7β on a vertical strike-slip fault. For this model the auxiliary plane perpendicular to the fault plane through the hypocenter is a neutral plane on which no focusing or defocusing would be expected. Focusing potential for the observation points lying near this plane will be V/β which is generally smaller than one, but may momentarily exceed one. Several recent workers have documented supersonic rupture for IV79 (Niazi, 1982; Olson and Apsel, 1982; Spudich and Cranswick, 1983; Archuleta, 1983). When the focusing potential value is larger than one the model predicts focusing. Values less than one of this parameter imply defocusing. Distribution of the observation sites of Table I relative to the source is shown in the Shakal and Sherburne article appearing in this report.

Figure I shows a plot of normalized PGA residuals against the computed focusing potential for the assumed rupture model as shown in Table I. Normalization of residuals is relative to one standard deviation of an individual observation. Almost all the data points near the left margin of the plot belong to the northern stations. This group, while showing scatter, clearly clusters near -1σ whereas the observations representing the southern station near the right margin cluster near $.5\sigma$. Ignoring the four central points shown by solid circles, a positive trend in agreement with the assumed unilateral southeast propagating rupture is suggested. The four central observation points do not lie on a linear trend defined by the two end clusters but display larger peak accelerations than predicted by focusing. On the contrary, the San Juan Bautista station, which has a more southerly azimuth, and therefore, higher focusing potential shows a negative residual. The four data points representing from left-to-right, observations at Santa Cruz, Capitola, Corralitos, and Watsonville, have several features in common. They all lie distant from and to the southwest of the source region within the Franciscan complex west of the San Andreas Fault. They are generally located in the sediment filled valleys or on sedimentary fans. Positioning of the source at the southern end of the rupture moves them slightly to the left on Figure I, and hence, further weakens the alignment. Therefore, focusing effect alone as prescribed by our simple model can not explain these four stations which do not lie close to the projection of fault trace. Perhaps, for

explaining the observed enhancement of peak accelerations at these four stations, other mechanisms related to propagation path or site conditions should be envoked rather than focusing. One of these four observations at Capitola constitute the only data of Table I with residual exceeding 2σ.

It must be noted that the scatter of data of Figure I would be expected, considering the very simple model by which the rupture is represented. Many factors, including the heterogeneity of rupture and propagation medium, departure from unidirectional and uniform rupture, and site conditions may be cited for producing the observed scatter. The latter factor, may have influenced the observations of Figure I in another way; as a result of the relative abundance of large embedded structures (10 stories and more) in the northwest azimuths. The observed PGA for these structures is somewhat lower than what is expected at freefield (Campbell, 1984, oral communication), hence, further enhancing the pattern.

Comparison with Previous Results

Disregarding a number of contrary observations in the southwest quadrant and probable effect of recording sites, the pattern of near source horizontal peak accelerations near the fault zone agrees with the focusing of seismic energy in the southeast direction. If this effect is produced by the unilateral propagation of the rupture front, the result would be somewhat different from those of a similar study (Niazi, 1982) of the 1979 Imperial Valley earthquake. In this study no focusing could be observed for the high frequency band associated with observations of PGA, but was documented for a low frequency band associated with peak velocities. To explain this dissimilarity, one may examine the spectral peculiarity of the Morgan Hill earthquake.

In Figure 2, the computed response spectra for the corresponding horizontal accelerograms recorded at Coyote Creek Dam (San Martin station) during August 1979 (250^{o}) and April 1984 (285^{o}) are compared. Apparently no documentation is available for reorientation of instruments in this interval (Shakal, 1984, personal communication) and the two orientations may, within measurement errors, be the same. While the possibility of ground disturbance at this site during April 1984 earthquake cannot be completely ruled out (Shakal et al., 1984b), the comparison of the two spectra at the same site is expected to minimize possible site effects. The spectra have been computed from the corrected data at 5 percent damping and for this comparison they represent approximately the smoothed Fourier amplitude spectra of the acceleration time histories.

The source region of the August 1979 earthquake lies on the same structure (the Calaveras fault) immediately to the southeast of the 1984 rupture (Bakun et al., 1984). The Coyote Creek Dam site lies in the focused zone of the latter, but in the defocused zone of the former source (Bouchon, 1982). The expected effect of focusing and defocusing on these two spectra of Figure 2 is such that in its absence the maxima might have been farther apart. However, even without adjustment for this effect, the Morgan Hill spectra peaks at frequencies nearly one octave lower than that of the August 1979 Coyote Lake earthquake; an indication that the spectral structure of 1984 earthquake was relatively enriched in low frequencies. Part of this low frequency enrichment may be related to a larger source size (M_L 6.2 vs 5.9) which is inversely scaled with corner frequency in the farfield for the Brune source model (Brune et al., 1979). However, the interpretation of spectral features in the near source is further complicated by the fact that the high frequency ground motion is mainly produced by the contribution of the closest segment of the source (Boatwright and Boore, 1982) as evidenced by inferred

saturation of PGA with magnitude in this region (Campbell, 1981). Moreover, visual inspection of accelerograms, particularly at Halls Valley and San Martin sites (Shakal et al., 1984b) suggests that PGA is generally associated with a low frequency ($\cong$ 1 Hz) wave package.

Conclusions

The pattern of near source peak ground motion residuals of the April 24, 1984, Morgan Hill earthquake in near-source region and within the fault zone may be explained by the focusing of seismic energy resulting from directivity of the source. However, only one observation falls outside the 2σ range of the predicted values. This observation was made at Capitola recording site which in the model adopted here is of low focusing potential. This and other observation points which do not fit the pattern satisfactorily, are generally located off the fault to the southwest of the San Andreas at distances over 30 km and within the region underlain by the late Mesozoic Franciscan complex.

The trial model which best explains the recorded peak ground accelerations near the end points of the fault requires the rupture front to travel at an average subsonic velocity of approximately $.7\beta$ in the southeast direction. Trials of larger than 0.7 of shear velocity tend to weaken the linear trend of Figure 1.

The observed dissimilarity of the focusing effect during the 1984 Morgan Hill and the 1979 Imperial Valley earthquakes may be explainable in terms of the low frequency enrichment of the 1984 signal. For the 1979 earthquake the effect was only detectable for lower frequency peak ground velocity (PGV) observations.

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TABLE I - Empirical Model
Comparison of PGA Residual and Focusing Potential ($\beta/V = 0.7$)

Station	Significant Distance (km)	Mean Horizontal PGA (g)	Residual /σ	Focusing Potential
Lexington Dam	25.0	0.020	-1.83	0.65
San Jose Santa Clara Cnty.Bl.	16.7	0.035	-1.68	0.48
Redwood City	50.3	0.010	-1.56	0.45
Livermore Valley	30.7	0.019	-1.51	0.43
Halls Valley	3.2	0.220	-1.29	0.54
Hayward	45.6	0.015	-1.10	0.41
Fremont	31.6	0.025	-1.01	0.42
San Jose Town Park Towers	15.4	0.060	-0.95	0.49
Belmont	39.2	0.020	-0.94	0.45
San Jose (GWB)	15.9	0.060	-0.90	0.49
Agnews Hospital	23.0	0.040	-0.86	0.60
Palo Alto VA	38.0	0.022	-0.85	0.44
Stanford Slac Survey Hill	43.3	0.021	-0.62	0.44
San Juan Bautista Fire Station	29.9	0.035	-0.57	1.98
San Jose Interchange	12.2	0.103	-0.49	.44
Stanford University	41.1	0.025	-0.48	.44
Palo Alto	37.0	0.030	-0.40	.44
Anderson Dam	3.8	0.355	-0.29	1.91
San Ramon	46.5	0.025	-0.24	.41
Gilroy #1	16.0	0.090	-0.23	1.95
Stanford Univ. SLAC Test Lab	44.0	0.031	0.03	.44
Gilroy Gavilan College	15.9	0.110	0.09	1.97
Apeel #2E	47.3	0.030	0.10	.41
Gilroy #7	13.7	0.150	0.32	2.23
Saratoga	27.0	0.070	0.36	.55
Apeel #1E	47.7	0.035	0.37	.42
Salinas	50.0	0.035	0.45	1.70
(L. Abut) San Justo Dam	34.4	0.056	0.47	2.20
(R. Abut) San Justo Dam	33.2	0.067	0.70	2.20
Corralitos	24.1	0.105	0.80	1.15
Watsonville	29.5	0.085	0.84	1.38
Hollister Differential Array	27.9	0.091	0.85	2.26
Gilroy #2	14.9	0.190	0.85	2.05
Hollister City Hall	32.2	0.077	0.87	2.26
Gilroy #3	14.4	0.200	0.87	2.05
Hollister Damler Residence	35.9	0.069	0.90	2.26
Hollister Warehouse	32.1	0.09	1.01	2.26
Gilroy #6	11.6	0.285	1.06	2.19
Santa Cruz	47.3	0.055	1.08	.81
Gilroy #4	12.6	0.300	1.29	2.11
Coyote Creek Dam	3.2	1.095	1.31	2.07
Capitola	39.2	0.125	2.04	0.96

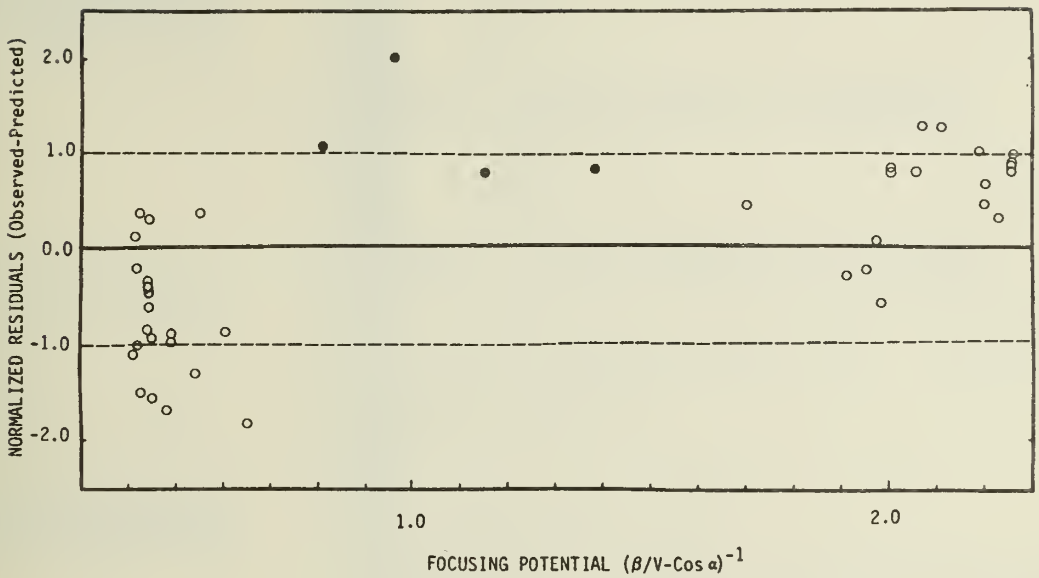

FIGURE 1

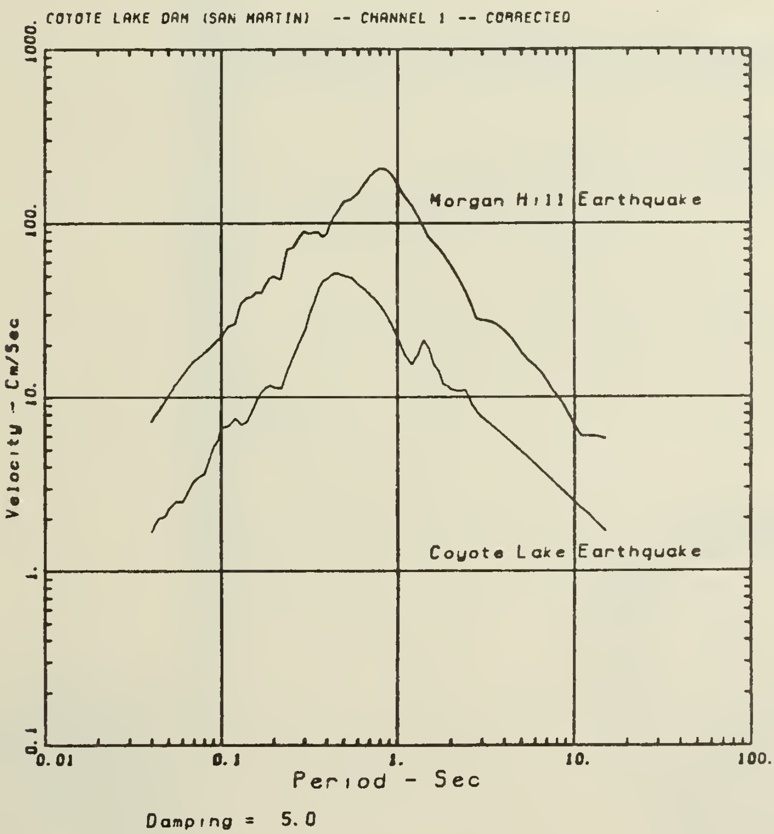

FIGURE 2